HIGHT

Distribution of heating in Synchronous converter armatures

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DISTRIBUTION OF HEATING IN SYNCHRONOUS CONVERTER ARMATURES

BY

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

EUGENE STUART HIGHT

ENTITLED DISTRIBUTION OF HEATING IN SYNCHRONOUS CONVERTER

ARMATURES

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

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C O N T E N T S.

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P R E F A C E.

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As the Science of Electrical Engineering advances, there is, perhaps, no electrical machine which demands more attention than the Synchronous Converter. Its applicability extends into practically every department of the Science and its uses are many and varied. And yet, so rapid has been the development of this machine, and the extension of its usefulness, that a great many of its characteristics are unknown to the Engineering world at large, even though they affect to a great extent the efficient application of the machine. It is due to lack of knowledge of some of the most important characteristics of the machine, that a great many engineers hesitate to use synchronous converters, and that, when they at last install the machines, they are at loss to intelligently interpret the seemingly eccentric behavior of their electrical systems. As a consequence, the converter is more of a mystery than of an aid to electrical engineers in general.

One of the most important of these characteristics is that of the variation and distribution of the heating in the armature coils with varying conditions of operation. It is due to this unusual variation, that many interesting and very practical phenomena take place. And it is upon the increase and decrease of this heating for certain conditions, that the fitness of a given machine for given conditions, is determined. Since the building of a machine for any certain installation, and its efficient operation after it is installed depend very largely upon this heating characteristic, an accurate knowledge of the behavior of the converter under given

conditions is valuable both to the designing and to the operating engineer.

It is the purpose of this paper to show the effect of varying conditions of operation, such as those due to leading or lagging currents of varying percent power factor, upon the variation and distribution of heating in the armature coils of converters of different phase ratings; to place this variation upon a comparative basis; and to discuss certain practical issues arising from the investigation.

Several articles were consulted in the preparation of this paper, references to which will be made in the discussion. Chief among those were: "Armature Heating in Synchronous Converters", by Dr. Steinmetz; "Rotary Converters", by Dr. E.J.Berg; and "Railway Converters", by E.J.Woodbridge. Ideas from all these sources are comprehended in this paper, and the results taken as being representative of the present development of Synchronous Converters.

May 27, 1910.

Eugene Stuart Hight.

D I C U S S I O N.

Distribution of Heating in Synchronous Converter Armatures.

The tendency of the development of the generation of electrical power is toward the advancement of alternating current. This is due, for most part, to the present idea of the centralization of generating stations and the consequent long distance transmission of the power to the centers of distribution. It is due also, to the rapid increase in electrical railway interests, which demand a constant supply of power to the line at more frequent intervals than it is possible to construct separate generating stations. In many instances, it is necessary to transmit the power considerable distances, and since the necessarily low generated voltages of direct current systems, and the extremely high line drop when any large amount of power is transmitted, are prohibitive factors where direct current is desired, it is necessary to generate alternating voltages, raise the voltage by transformers, reduce it at the end of the line, and procure direct current by the use of some system of conversion. This is the tendency of present day development.

The system of conversion of alternating current to direct current, which is most economical and practical, and hence, most generally used, is that procured by the use of synchronous converters. Now, alternating voltage is generated at from single phase to six phase, with possible practical exclusion of five phase. Also, although it is possible to use six phase converters on three phase systems and vice versa, it is most general practice to use a given

phase converter with a line of the same phase rating. At all events, all phases from one to six are being taken up in converter construction, and in an investigation of converter operation, it is necessary to consider machines of practically all the above mentioned phases.

In the case of a machine having any one of the generally used phase ratings, the conditions under which it may operate may be extremely varied in different installations; but, owing to the general construction of the machine, the one condition which affects its operation to the greatest extent is that of use on heavily reactive transmission lines or other systems of like nature. All the other varying conditions, such as a changing load or an unstable line, will, of course, affect the operation of the machine after it is installed; but the factor which determines the converter for a given set of conditions, and which determines whether or not machines on hand may be used to meet new conditions, is that of the power factor of the system upon which the machine is to operate. Consequently, in an investigation of a given converter, it is extremely necessary to determine its action under varying conditions of power factor.

Now, synchronous converters of a given type of construction, no matter of what phase rating they may happen to be, will all have the same characteristics under varying conditions of power factor; but all of these characteristics will not be of the same relative magnitude or importance. It is due to this fact that machines of relatively higher economy under certain conditions, will become vastly less efficient than other uneconomical machines under different conditions. Hence the mystery of the operation of synchronous converters.

This change in applicability of given machines with change in the power factor of the systems with which they are to be

used, is due to variation of heating in the coils of the converter armatures. This variation has greatest effect upon the rating of the machines for differing conditions of operation and is the cause, for the most part, of such phenomena as the uneven over-heating in the armature coils, the breakdown of machines when operated far under the manufacturer's rating, and so on. All of these are, in reality, due to the ignorance of the operating engineer, who does not appreciate the effect of the heavily reactive system upon the heating in the machine under his charge, and consequently endeavors to use a machine which is not at all applicable to the conditions.

This variation of armature heating follows a very definite law as the power factor of the system changes; and it is probable that a discussion of this law and a representation of its application will be of interest both to operating and to designing engineers, who have anything to do with synchronous converters. The following theory is that upon which the investigation is usually made and is readily interpreted as the symbolical statement of the law which is followed by the variation of armature heating. A knowledge of the essential principles of the construction and operation of a synchronous converter is pre-supposed in the development of this theory.

The armature winding of the present day converter is a continuous winding of either the simplex lap or wave style. The multiplex windings are not well adapted for use in converters due to the complex conditions arising from the increased number of leads to the collector rings and to the commutator segments. There are then, for the direct current in the armature, two paths when the wave winding is used, or a number of paths equal to the number of poles in the field when the lap winding is used. The method of

connecting the commutator segments corresponds to that used in any direct current generator of the usual type; connections to each segment being made from between the corresponding coils on the armature. The collector rings are connected each to a certain part of the armature in such a way that the points of connection will separate the armature winding into as many parts as there are collector rings. Thus, we have,

Single phase,	two rings,	two equal parts of the winding;
Three phase,	three rings,	three equal parts of the winding;
Quarter phase,	four rings,	four equal parts of the winding;
Six phase,	six rings,	six equal parts of the winding;

And so on.

The method is shown in Figure I, which illustrates the essential parts of a three phase connection.

Due to the fact that, for each phase, the armature connections are constant for any machine, it follows that a definite ratio exists between the alternating current voltage and the direct current voltage. This ratio is determined as follows:

Suppose an armature to be rotating in a field produced by "k" poles, and that it has "s" turns per pole; suppose also, that an effective alternating voltage of "e" volts is generated in each turn due to the field excitation and to the revolution of the armature. The total turns upon the armature are "ks". Now, if "n" is the number of collector rings, there are "n" divisions in the armature winding, and also, there are $\frac{ks}{n}$ turns per division or per phase, since "n" is also the phase rating in the case of any polyphase machine except quarter phase. The voltage per phase is the vector sum of the voltages in the separate turns of each phase, as is indicated in Figure 2, where E_a, the voltage for each of the three

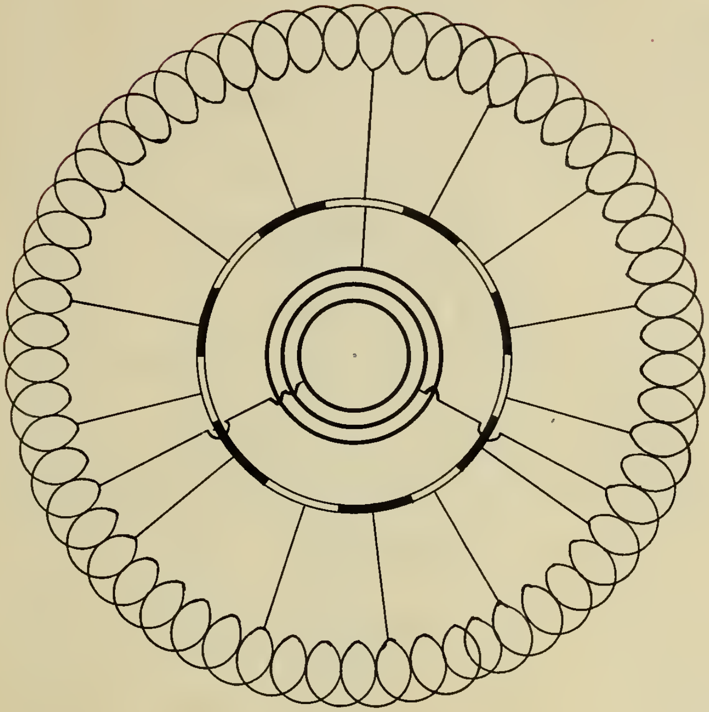

Figure 1.

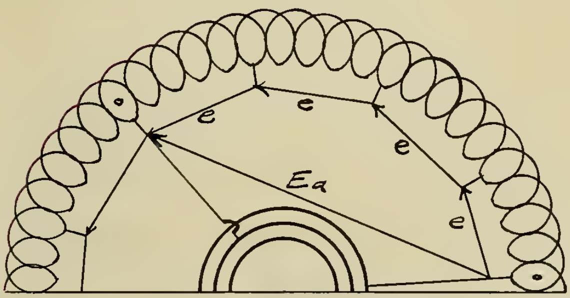

Figure 2

phases indicated, is the vector sum of the voltages, "e", "e", generated in each phase. The numerical sum of these voltages per phase is $\frac{Kse}{n}$, which follows directly. Since the turns are arranged about the circumference, E_a, the phase voltage, is represented by a vector chord, subtending an arc of length equal to $\frac{Kse}{n}$, where "e" is the vector voltage in each turn. This arc equals $\frac{2\pi}{n}$ radians. Then the length of the chord follows directly, and

$$E_a = \frac{2Kse}{2\pi} \sin\frac{\pi}{n}$$

$$= \frac{Kse}{n} \sin\frac{\pi}{n}$$

where E_a is the effective value of alternating voltage per phase. Now, in any converter, the direct voltage is equal to the maximum value of the single phase alternating voltage. Then

$$E_D = \frac{\sqrt{2}\,Kse}{\pi} \sin 90^\circ$$

$$= \frac{\sqrt{2}\,Kse}{\pi}$$

Then the ratio,

$$\frac{E_a}{E_D} = \frac{\frac{Kse}{\pi} \sin\frac{\pi}{n}}{\frac{\sqrt{2}\,Kse}{\pi}}$$

$$= \frac{1}{2}\sqrt{2} \sin\frac{\pi}{n}$$

for all phases, where "n" is, as noted above, the number of collector rings.

The current ratio in each phase, however, is much different, and more factors enter into its calculation. It has been found that the alternating voltage has the value,

$$E_a = \frac{E_D}{2}\sqrt{2} \sin\frac{\pi}{n}$$

Due to the vector displacement of the alternating current in the different phases in the armature, the line current on the alternating side, has the value,

$$I_a = 2I \sin\frac{\pi}{n}$$

(G.E. Review, Vol. X, No. 2)

where I is the alternating current in each phase. The total alternating power input will be

$$P_a = E_a i n$$
$$= \frac{E_a i_a n}{2 \sin \frac{\pi}{n}}$$

Now, assuming a direct current power output equal to the alternating current power input, that is, assuming zero losses in the machine,

$$P_a = P_D$$

But

$$P_D = E_D i_D$$

where i_D is the direct line current.

Then

$$E_D i_D = \frac{n E_a i_a}{2 \sin \frac{\pi}{n}}$$
$$= \frac{n E_D i_a \sin \frac{\pi}{n}}{2\sqrt{2} \sin \frac{\pi}{n}}$$
$$= \frac{n E_D i_a}{2\sqrt{2}}$$

Then the ratio,

$$\frac{i_a}{i_D} = \frac{2\sqrt{2}}{n}$$

which is seen to be the ratio of the alternating line current to the direct line current. Now,

$$i_a = 2i \sin \frac{\pi}{n}$$

and

$$i_D = 2 i_c$$

where i_c is the direct current in each circuit of a two circuit winding. Then

$$\frac{2i \sin \frac{\pi}{n}}{2i_c} = \frac{2\sqrt{2}}{n}$$

and

$$\frac{i}{i_c} = \frac{2\sqrt{2}}{n \sin \frac{\pi}{n}}$$

which is seen to be the ratio of the effective alternating current in the phase winding to the direct current in that winding. Then the maximum alternating current in the winding is

$$i_m = \frac{4 i_c}{n \sin \frac{\pi}{n}}$$

In Figure 3, an armature is represented as rotating in a field produced by two poles, and is shown in an instantaneous position. Let α be the angle in electrical degrees, between the center of a phase winding and the plane of commutation, which last is assumed neutral. Let φ be the angle of lag between the alternating current and the counter-generated voltage in any given turn. Let β be the angular displacement of any other coil in the section from the center of the phase section of winding. (A.I.E.E.Vol.27,No.2)

Now, considering the instantaneous value of the alternating current in the coil displaced by angle φ from the center coil of the phase section. When this coil passes a point, displaced by an angle $\frac{\pi}{2}$ (electrical) from the plane of commutation, the alternating voltage will, at that instant be a maximum. The alternating current at the same instant will be,

$$i_s = i_m \cos\varphi$$

and

$$i_{max} = \frac{i_s}{\cos\varphi}$$

As the coil in question moves from the point displaced by angle $\frac{\pi}{2}$ from the plane of commutation, the generated voltage will vary as the cosine of the angle of displacement. That is,

$$e = e_m \cos\left(\frac{\pi}{2} - \alpha - \varphi\right)$$

Now, since the resistance of the coil is constant, the variation of the current follows the same law, and

$$i_s = i_m \cos\left(\frac{\pi}{2} - \alpha - \varphi\right)$$

Then

$$i_s = \frac{4 i_c \cos\left(\frac{\pi}{2} - \alpha - \varphi\right)}{n \sin\frac{\pi}{n}}$$

where i_s is the instantaneous value of alternating current in the coil which is displaced by the angle φ from the center of the phase section. Then

$$i_s' = \frac{4 i_c \cos\left(\frac{\pi}{2} - \alpha - \varphi\right)}{n \sin\frac{\pi}{n} \cos\varphi}$$

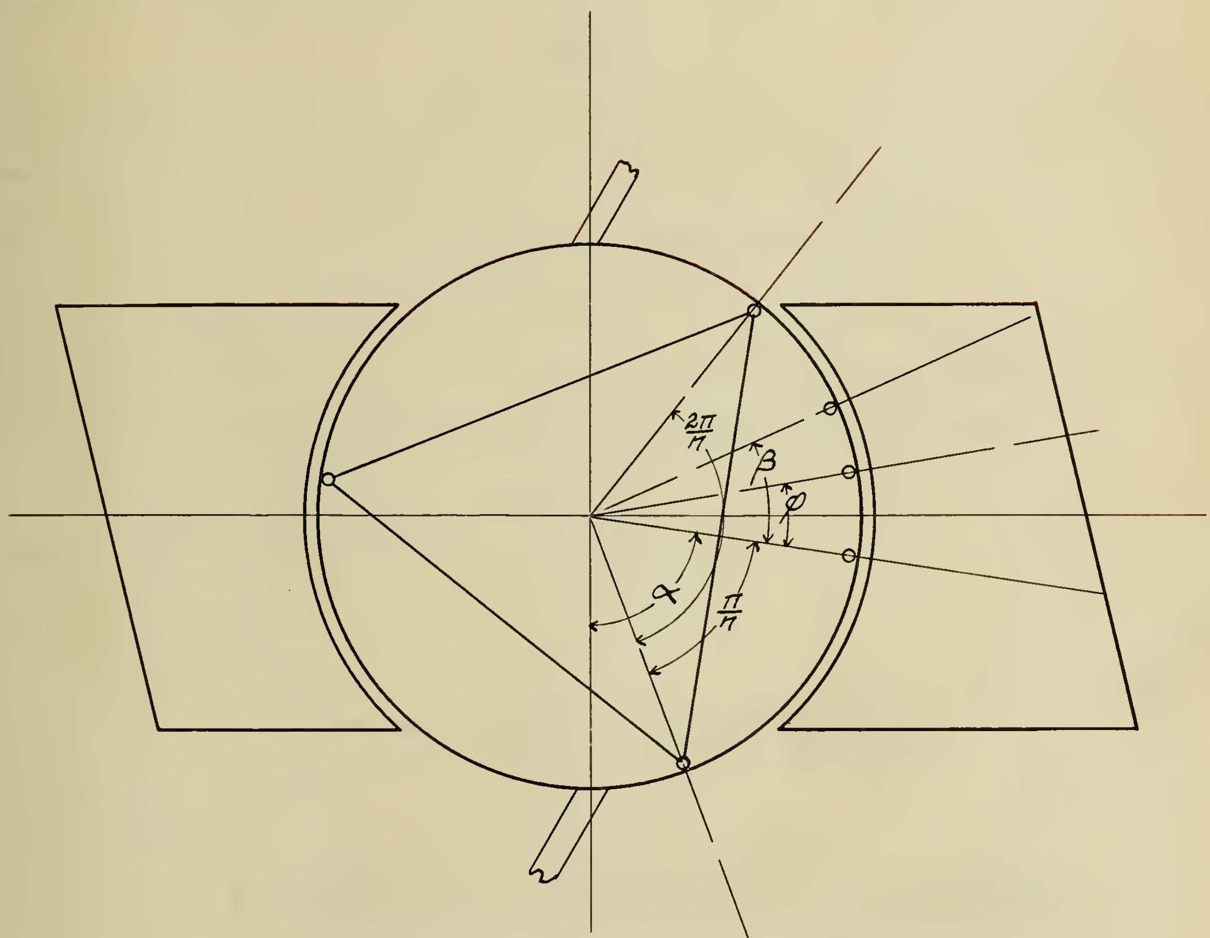

Figure 3.

which is the instantaneous value of the alternating current in the center coil of the phase section.

Now, the resultant current is the numerical difference between the values of direct current and alternating current in the coil under consideration. Then

$$i_r = i_c\left(1 - \frac{4\sin(\alpha+\phi)}{n\sin\frac{\pi}{n}\cos\phi}\right)$$

and i_r is the resultant instantaneous current. If I_D is the direct line current, then

$$i_c = \frac{I_D}{2m}$$

in an armature with an $2m$-circuit winding, where "m" is the number of pairs of poles in the case of a lap wound armature, and is constant and equal to unity in the wave wound machine.

Suppose the resistance of the coil is unity. Now, since the heating in the coil varies directly as the product of the resistance into the square of the resultant current, then

$$KH = i_r^2 r$$

where "r" is the resistance of the coil. Then, if "r" is equal to unity,

$$KH = \frac{I_D^2}{4m^2}\left[1 - \frac{4\sin(\alpha+\phi)}{n\sin\frac{\pi}{n}\cos\phi}\right]^2$$

and

$$KH = \frac{I_D^2}{4m^2}\left[.25 - \frac{2\sin(\alpha+\phi)}{n\sin\frac{\pi}{n}\cos\phi} + \frac{4\sin^2(\alpha+\phi)}{n^2\sin^2\frac{\pi}{n}\cos^2\phi}\right]\times 4$$

where KH represents the heating in the center coil in any position from $\phi=0$ to $\phi=\pi$ in electrical units of angular measurement. Then,

$$KH = \frac{I_D^2}{m^2}\left[.25 - \frac{2\sin(\alpha+\phi)}{n\sin\frac{\pi}{n}\cos\phi} + \frac{4\sin^2(\alpha+\phi)}{n^2\sin^2\frac{\pi}{n}\cos^2\phi}\right]$$

Now, suppose the machine is operated as a direct current generator, delivering I_D amperes to the direct current line. The

heating in each coil of any section is then proportional to $\frac{I_D^2}{m^2}$
Then the ratio of the heating in the coil under consideration when the machine is run as a converter, to that when the same direct line current is mechanically generated in the armature, is

$$y = \frac{i_r^2 r}{\frac{I_D^2}{m^2} r}$$

and

$$y = \left[.25 - \frac{2\sin(\alpha+\varphi)}{n\sin\frac{\pi}{n}\cos\varphi} + \frac{4\sin^2(\alpha+\varphi)}{n^2\sin^2\frac{\pi}{n}\cos^2\varphi}\right]$$

Then the corresponding ratio of the average heating for any coil distant β degrees from the center of the phase section is

$$y' = \frac{1}{\pi}\int_{\beta}^{\pi+\beta} y\,d\alpha$$

Then

$$y' = \frac{1}{\pi}\int_{\beta}^{\pi+\beta}\left[.25 - \frac{2\sin(\alpha+\varphi)}{n\sin\frac{\pi}{n}\cos\varphi} + \frac{4\sin^2(\alpha+\varphi)}{n^2\sin^2\frac{\pi}{n}\cos^2\varphi}\right]d\alpha$$

which by easy stages of integration, reduces to the equation,

$$y' = \left[.25 - \frac{4}{\pi n\sin\frac{\pi}{n}}(\cos\beta - \sin\beta\tan\varphi) + \frac{2\sec^2\varphi}{n^2\sin^2\frac{\pi}{n}}\right]$$

where y' is the average heating ratio for any coil distant β degrees from the center; n is the number of collector rings; φ is the angle of lag; and $-\varphi$ would be the angle of lead.

It is easily seen that to determine the average heating ratiofor any phase section, and consequently for the armature for balanced loading, it is only necessary to find the mean heating ordinate over the total angular space occupied by the phase winding. This is done as follows:

$$y_{av} = \frac{n}{2\pi}\int_{-\frac{\pi}{n}}^{\frac{\pi}{n}} y'\,d\beta$$

$$Y_{av} = \frac{n}{2\pi}\int_{-\frac{\pi}{n}}^{\frac{\pi}{n}}\left[.25 - \frac{4}{\pi n \sin\frac{\pi}{n}}\left(\cos\beta - \sin\beta\tan\phi\right) + \frac{2\sec^2\phi}{n^2\sin^2\frac{\pi}{n}}\right]d\beta$$

which reduces to the equation,

$$Y_{av} = \left[-.155 + \frac{2}{n^2\sin^2\frac{\pi}{n}}\left(1+\tan^2\phi\right)\right]$$

and Y_{av} is the average heating ratio for the total armature at balanced loading.

It is now desired to find the variation of the permissible direct current rating with power factor. When $\phi = 0$, which is the condition under which the rating is made,

$$Y_{av}^{0} = \left[-.155 + \frac{2}{n^2\sin^2\frac{\pi}{n}}\right]$$

Now, if as before, I_D is the direct line current; and if m is unity; the actual heating H is proportional to

$$\Sigma = I_D^2\left[-.155 + \frac{2}{n^2\sin^2\frac{\pi}{n}}\right]$$

$$= I_D^2 Y_{av}^{0}$$

When ϕ varies,

$$\Sigma = I_D^2 Y_{av}$$

Then let

$$I_D^2 Y_{av} = Y_{av}^{0}$$

Then

$$I = \left[\frac{Y_{av}^{0}}{Y_{av}}\right]^{\frac{1}{2}}$$

$$= \left[\frac{\left[-.155 + \frac{2}{n^2\sin^2\frac{\pi}{n}}\right]}{\left[-.155 + \frac{2}{n^2\sin^2\frac{\pi}{n}}\left(1+\tan^2\phi\right)\right]}\right]^{\frac{1}{2}}$$

and

$$I = \left[Y_{av}^{0}\left(Y_{av}^{0} + \frac{2\tan^2\phi}{n^2\sin^2\frac{\pi}{n}}\right)^{-1}\right]^{\frac{1}{2}}$$

from which equation, the relation of rating to power factor may be determined.

From the equations for y' and y_{av}, it is possible to determine the curves showing the relation of the heating ratio to change in power factor and to variation in phase. From a general inspection of the equation for y_{av}, it is seen that for any constant value of ϕ , the heating ratio approaches a minimum as the number of collector rings increases. If the equation is investigated for a minimum value of y_{av}, the following results are obtained:

$$\frac{d(y_{av})}{d(n^{-1})} = \frac{4(1+\tan^2\phi)\sin^2\frac{\pi}{n} - 4\pi(1+\tan^2\phi)n^{-2}\sin\frac{\pi}{n}\cos\frac{\pi}{n}}{\sin^4\frac{\pi}{n}}$$

$$= 0$$

$$\sin\frac{\pi}{n} = \frac{\pi}{n}\cos\frac{\pi}{n}$$

$$\tan\frac{\pi}{n} = \frac{\pi}{n}$$

$$\sec\pi n^{-1} = \pm 1$$

$$\cos\pi n^{-1} = 1$$

$$\pi n^{-1} = 0$$

$$n = \infty$$

and the minimum value of the heating ratio (average) occurs with infinite phase, which is, of course, never practically obtained or even desired.

Also, the following determination may be made:

$$y_{av} = \frac{2(1+\tan^2\phi)}{n^2\sin^2\frac{\pi}{n}} - .155$$

For any constant percent power factor,

$$D = 2(1+\tan^2\phi), \qquad K = -.155$$

Then

$$y_{av} = \frac{D}{n^2\sin^2\frac{\pi}{n}} - K$$

from which the curves of the variation of y_{av} with "n" may be determined.

The evaluation of the above equations for the different phases to be investigated, is the result of the direct substitution

of the value of "n", corresponding to any phase for which the heating ratios are desired. The results are definite, from inspection, for any definite value of "n".

For the value $n = \infty$, however, the expression containing $\sin\frac{\pi}{n}$ is an indeterminate of the form $\frac{0}{0}$, and must be evaluated by a scheme of differentiation. It is desired first, to evaluate

$$y = n^2 \sin^2 \frac{\pi}{n}\Big]_{n=\infty}$$

This may be thrown into the form, with "n" varying, of

$$y = \frac{\sin^2 \pi n^{-1}}{n^{-2}}$$

The first differentials with respect to n^{-1} of both numerator and denominator, are then taken separately, and

$$\frac{d(\sin^2 \pi n^{-1})}{d(n^{-1})} = 2\pi \sin(\pi n^{-1})\cos(\pi n^{-1})$$

(Townsend and Goodenough, p.342)

$$\frac{d(u^{-2})}{dn^{-1}} = 2n^{-1}$$

Then

$$y_1 = \frac{\pi \sin \pi n^{-1} \cos \pi n^{-1}}{n^{-1}}$$

which evaluated for $n=\infty$ results again in $\frac{0}{0}$, and is indeterminate. The second derivatives are then taken and

$$\frac{d(\pi \sin \pi n^{-1} \cos \pi n^{-1})}{d(n^{-1})} = -\pi^2(\sin^2 \pi n^{-1} - \cos^2 \pi n^{-1})$$

also

$$\frac{d(n^{-1})}{d(n^{-1})} = 1$$

Then

$$y_2 = -\pi^2(\sin^2 \pi n^{-1} - \cos^2 \pi n^{-1})$$

and this equation, evaluated for $n=\infty$, is

$$y_2 = \pi^2 \cos^2(0)$$
$$= \pi^2$$

So that

$$y = n^2 \sin^2 \frac{\pi}{n}\Big]_{n=\infty} = \pi^2$$

In a similar manner, the equation

$$y = n \sin \frac{\pi}{n}$$

may be evaluated for $n=\infty$. As follows:

$$y = n \sin \frac{\pi}{n}$$

Then

$$\frac{d(\sin \pi n^{-1})}{d(n^{-1})} = \pi \cos \pi n^{-1}$$

and

$$\frac{d(u^{-1})}{d(n^{-1})} = 1$$

then

$$y_1 = \pi \cos \pi n^{-1}$$

and this equation, evaluated for $n=\infty$, is

$$y_1 = \pi \cos(0) = \pi$$

So that

$$y = n \sin \frac{\pi}{n} \Big]_{n=\infty} = \pi$$

A slight investigation of the ratio equations shows that the ratio values for leading current, that is, when ϕ is negative, are exactly symmetrical with those for positive values of ϕ, about the line $\beta=0$, in the case of each phase rating. The average ratios are, of course, the same for any given power factor and phase rating, whether ϕ is positive or negative, due to the presence of the $\tan^2$ factor. For this reason, no consideration is given the leading power factor values, since with the same percent power factor, there is no change in the results, and no difference in distribution, except an actual symmetrical shift of the ratio values about the line $\beta=0$, in each phase section.

It has been mentioned that the foregoing theory relates

entirely to conditions of balanced loading upon the different phases. This is the theoretical operating condition, and is the condition upon which most machines are designed and rated. If, however, a polyphase machine must operate under unbalanced load conditions, a very convenient assumption may be made. The machine may be considered as two single phase converters or as a polyphase converter and a single phase converter. Since a single phase converter may be expected to operate fairly satisfactorily, the combination may be expected to operate at an appreciable efficiency, even though the efficiency can not be so high as that of the complete machine on balanced conditions. The effect of the unbalancing upon the heating in the machine does not depend so much upon the amount of unbalancing as it does upon the percent power factor of the unbalanced phases. No attempt will be made to calculate the effect upon the heating ratio of the unbalancing; but such points as are apparent will be taken from the results for balanced loading. (Steinmetz,"Elements",p.296)

The evaluation of the ratio formulae, and the resulting curves will be found in the Appendix to this discussion.

From these results, it is possible to draw a great many conclusions. However, only a few of the most important will be discussed, in order of their importance. They will be taken up as follows: Copper Losses and Rating, Rating Limit for Economical Construction, and Three Phase versus Six Phase Operation.

A number of interesting conclusions regarding the copper losses in converter armatures may be drawn from the comparison curves. The copper losses vary as the square of the resultant current, and the curves showing the variation of the heating ratio are exactly the same as those which show the ratio of copper losses, when the machine is operated as a converter and as a direct current

generator.

It is plain from an investigation of the comparison curves, that, as the percent power factor decreases, the specific heating ratio increases in any machine of a given phase rating. Also, at the same time, the average ratio increases. A glance at the distribution curves shows that, as the percent power factor decreases, the heating, which is a maximum at the winding taps at unity power factor, is increased on one side of the taps to a greater extent than it is on the other side. Due to this increase, the heating is crowded into a few coils on one side of the ring connection, and these coils are greatly over-heated. The maximum heating in the coils close to the taps, increases much more rapidly than the average heating in the phase section.

Now, when a machine is built, its rating is made on the assumption of operation on balanced loading and at 100% power factor. Due to the desire for economical construction, the copper in the armature is not capable of carrying extremely high currents for any length of time. Consequently, when a machine with a given rating is operated at full load on a low power factor, it is more of a mystery why it does not at times burn up, rather than why it occasionly does.

The Rating-Power Factor comparison curve shows some interesting data on this point. For instance, if a three phase machine is operated on 85% power factor, its load should not exceed three-quarters its rated output, if the copper losses are to be kept constant. A six phase machine should not be loaded to exceed 65% of its rating, under the same conditions. Converters are constructed however, so that an overload may be carried; and it is clear, that when a machine is carrying full load on a low power factor, it is

running constantly on its overload capacity.

Because of these points, it is necessary to investigate the conditions under which a machine is to operate, before a machine with proper rating can be chosen. And it is necessary to install a machine rated above the expected load if the power factor varies to any extent from unity.

The Heating-Phase Rating comparison curve shows another interesting point. It has been observed that, as the number of collector rings increases, the average heating for any given power factor decreases and the minimum ratio is found when "n" is infinite. It may be seen from this curve, that, after a point is reached where "n" is equal to six, the variation of ratio from the value for "n" equal to six to that for "n" infinite, is exceedingly small. Due to the fact that additional collector rings and phase sectioning of the armature mean additional cost, while after the six phase is reached, the gain in reduction of heating is very small, it follows that, beyond six phase, it is not economical to construct machines for practical operation. And the loss in economy increases rapidly with increase in the value of "n".

One very valuable conclusion which may be derived from the fore-going investigation is that, as the number of collector rings increases, the permissible rating for the same load increases. This is of most practical importance in the case of three and six phase converter operation. If a three phase machine is operated on 80% power factor, its permissible rating is about 70% of full rating. With a six phase machine under the same conditions, the permissible rating is about 60% of full rating. A glance at the average heating curves shows that for 80% power factor, the average heating for six phase is about 66% of the average heating for three phase under the

same load. It follows, then, that a six phase machine may be rated from 75% to 100% higher than the same machine operated three phase under the same conditions. Thus, a great many three phase converters operating at poor efficiency, could be changed into very efficient machines, by the application of three more collector rings and a little additional wiring. Although this application does not consider the losses in the machine, and the influence upon the heating of hunting, and the change in the intensity of harmonics with change in voltages, it may be considered to be fairly accurate, since the corresponding losses in the six and three phase machines are approximately proportional. (A.I.E.E.,Vol.27,No.2)

If the distribution curves in the separate phase sections are considered, it is found that all the curves have the same general shape; those corresponding to the lower values of "n", being farther developed owing to the greater range of the phase angle. In as much as the constant coefficients for each phase change with variation of "n", the curves do not coincide. The distribution follows a transcendental law, which is a constant for all values of "n" between unity and infinity.

It may be observed that, for unity power factor, the heating is a maximum at the phase taps in the winding; and that, as the power factor decreases, the heating is shifted from the bars in the armature on one side of the tap to those on the other side. And it is to be noted that at times, the heating on the latter side is increased 100% to 200% with a corresponding decrease in radiating surface, due to the crowding of the heating losses into a few bars.

An interesting point which may be noted is that, as the power factor decreases, the minimum heating in a phase section shifts from the center along the section toward one of the taps, as the heating increases in the other end of the section. For the

larger values on "n" and ϕ, this minimum finally reaches the tap, and the average heating in the coil immediately begins to rise more rapidly. This does not have appreciable effect upon the average ratio however, since the rate of increase changes slowly.

In conclusion, it follows that the distribution of the heating in the armature windings of synchronous converters depends upon the application of a definite law. Also, that this distribution has great effect upon the design, rating, and operating of converters. And consequently, an investigation of this law and of the variation of the heating losses in the phase section of an armature winding, results in a clearing up of much of the "mystery", which attends the practical application of converters to modern conditions of operation.

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A P P E N D I X.

A P P E N D I X.

Thruout the numerical calculation of the investigation, the armature has been considered to be rotating in a field produced by two poles, and thus having two circuits, whether wave or lap wound. The results of the calculation have been tabulated as far as possible, for the most rapid reference; and the curves depend directly upon the tables for their evaluation. The calculation has been made for each of single, quarter, three, six, twelve, and infinite values of phase rating, and for percent values of power factor from 100 to 50, by intervals of 5%, and for values of 5%. The angular displacement of the coil, that is, angle β, has been taken at intervals of 5 degrees. Since balanced loading is assumed, the heating ratio for but one phase winding on each machine, has been calculated, since the value for the other windings will be exactly similar.

The evaluation of the ratio formulae follows the substitution of the value of "n", corresponding to the phase rating for which the ratios are desired, as before explained. This method of procedure results in the following special equations:

Single Phase. $n = 2$

$$Y' = [.75 - .635(\cos\beta - \sin\beta\tan\phi) + .5\tan^2\phi]$$

$$Y_{av} = [.345 + .5\tan^2\phi]$$

Three Phase. $n = 3$

$$y' = \left[.546 - .489(\cos\beta - \sin\beta\tan\phi) + .296\tan^2\phi\right]$$

$$y_{av} = \left[.141 + .296\tan^2\phi\right]$$

Quarter Phase. $n = 4$

$$y' = \left[.501 - .450(\cos\beta - \sin\beta\tan\phi) + .251\tan^2\phi\right]$$

$$y_{av} = \left[.096 + .251\tan^2\phi\right]$$

Six Phase. $n = 6$

$$y' = \left[.472 - .424(\cos\beta - \sin\beta\tan\phi) + .222\tan^2\phi\right]$$

$$y_{av} = \left[.062 + .222\tan^2\phi\right]$$

Twelve Phase. $n = 12$

$$y' = \left[.455 - .409(\cos\beta - \sin\beta\tan\phi) + .205\tan^2\phi\right]$$

$$y_{av} = \left[.050 + .205\tan^2\phi\right]$$

Infinite Phase. $n = \infty$

$$y' = y_{av} = \left[.0475 + .202\tan^2\phi\right]$$

The equations for the variation of rating, result as follows:

Single Phase.

$$I = \left[\frac{.345}{.345 + .5\tan^2\phi}\right]^{\frac{1}{2}}$$

Three Phase.

$$I = \left[\frac{.141}{.141 + .296\tan^2\phi}\right]^{\frac{1}{2}}$$

Quarter Phase.

$$I = \left[\frac{.096}{.096 + .251\tan^2\phi}\right]^{\frac{1}{2}}$$

Six Phase.

$$I = \left[\frac{.062}{.062 + .222\tan^2\phi}\right]$$

Twelve Phase.

$$I = \left[\frac{.050}{.050 + .205\tan^2\phi}\right]$$

Infinite Phase.

$$I = \left[\frac{.0475}{.0475 + .202\tan^2\phi}\right]$$

From these equations the following tables were compiled:

Table I.--which gives the values of the heating ratio for single phase, for any coil distant β_s degrees from the center coil, and for any of the calculated percent power factors.

Table II.-which gives the corresponding values for three phase.

Table III.which gives the corresponding values for quarter phase.

Table IV.--which gives the corresponding values for six phase.

Table V.---which gives the corresponding values for twelve phase.

Table VI.--which gives the corresponding values for infinite phase.

Table VII.-which gives the variation of average heating ratios, for each value of percent power factor, with the number of collector rings.

Table VIII.which gives the permissible rating for any percent power factor in any of the generally used phases, in percent of the rating at 100% power factor.

Table IX.---which gives the angles of phase difference corresponding to definite values of percent power factor.

Table X.----which gives the values of the maximum heating ratio, for various percent power factors and various values of "n".

Table XI.---which gives the variation of the A.C.-D.C. voltage ratio with the change in phase rating.

It will be observed that in the cases of all values of percent power factor except 5%, the value of the heating ratio in the table is 1000 times the actual ratio. This method avoids the use of decimal points which would necessarily complicate the tables. In the case of the 5% power factor the tables give the actual ratio.

From the first six of these tables, the polar distribution curves were plotted. The method of plotting is as shown in the sample sheet, and the procedure is as follows: The section center is taken on any radial line. From this line, on each side, the angular distance corresponding to half the phase section is laid off, as shown by the numbers, zero degrees to 45 degrees. On each 5 degree radial line, the corresponding heating ratio is laid off, and the curve shown at "a" is drawn. This is the distribution curve. The circle "b", is then drawn at a distance from zero equal to the average ordinate for any section. This is the average curve. On each sheet, at the unit distance from the zero circle, a curve is drawn which represents the equivalent heating due to the direct line current, and is the basis of comparison for the ratio. Due to the symmetry existing between the polar curves for lag and lead angles of constant power factor, but one curve for leading current is shown. This indicates the shift of heating from one side of the winding tap to the other, for shift of φ from positive to negative.

The rectangular curves were plotted directly from the tables. The method of procedure is clear from a comparison of the tables and curves.

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T A B L E S.

Table I.

Single Phase.

Variation of Heating Ratio with Power Factor.

β	Per cent Power Factor Lagging										
	100	95	90	85	80	75	70	65	60	55	50	5
90	750	595	560	547	553	574	622	689	790	936	1153	187.08
85	695	540	505	493	498	524	569	635	737	885	1099	187.08
80	640	489	455	444	450	477	523	591	694	844	1060	187.17
75	585	437	405	396	402	432	479	551	664	806	1023	187.37
70	533	390	366	354	352	375	444	518	624	778	1005	187.63
65	482	346	319	316	326	362	414	481	600	758	986	187.99
60	432	305	282	282	296	336	391	471	586	748	970	188.46
55	386	269	251	255	272	316	376	469	579	747	987	189.01
50	342	235	222	231	251	300	365	453	578	753	1000	189.94
45	300	206	189	213	237	293	361	456	587	769	1024	190.32
40	263	183	182	201	230	292	366	468	614	793	1059	191.11
35	229	164	170	195	228	297	378	484	630	827	1102	191.98
30	199	149	162	193	231	307	395	509	661	879	1152	192.84
25	174	139	161	199	242	326	420	541	703	917	1213	193.82
20	144	136	164	209	258	350	452	580	749	974	1281	194.82
15	136	135	164	225	278	379	481	624	802	1036	1344	195.86
10	125	143	188	248	307	417	533	677	864	1108	1418	196.90
5	116	152	206	272	338	457	579	733	927	1182	1524	198.02
0	115	169	232	306	377	504	635	796	1000	1265	1620	199.11
5	116	188	260	342	418	553	693	861	1075	1350	1718	200.23
10	125	215	286	384	467	611	757	935	1156	1442	1822	201.33
15	136	243	340	427	516	669	829	1008	1238	1534	1926	203.42
20	144	278	376	479	572	734	894	1088	1327	1632	2035	203.49
25	174	317	421	531	630	800	968	1169	1415	1731	2145	204.53
30	199	347	470	587	691	869	1043	1251	1507	1820	2256	205.54
35	229	402	522	625	754	939	1100	1336	1598	1931	2366	206.48
40	263	451	578	707	820	1012	1200	1400	1682	2033	2477	207.41
45	300	502	645	769	887	1085	1279	1506	1783	2131	2586	208.28
50	342	555	694	833	955	1160	1357	1591	1874	2229	2672	209.06
55	386	611	755	899	1024	1234	1436	1675	1963	2325	2795	209.77
60	432	667	816	964	1092	1306	1513	1754	2048	2416	2904	210.41
65	482	724	877	1028	1160	1378	1588	1833	2132	2504	2986	210.97
70	533	782	932	1092	1226	1447	1660	1908	2207	2586	3069	211.43
75	585	841	999	1156	1292	1516	1731	1981	2286	2664	3157	211.80
80	640	890	1059	1218	1354	1580	1797	2051	2356	2736	3233	212.11
85	695	956	1117	1277	1414	1642	1859	2115	2421	2803	3299	212.31
90	750	1013	1174	1335	1471	1699	1918	2173	2480	2864	3357	212.42
Ave.	345	435	462	536	607	784	865	1026	1230	1495	1845	199.34

Table II.

Three Phase.

Variation of Heating Ratio with Power Factor.

β	Percent Power Factor Lagging.										
	100	95	90	85	80	75	70	65	60	55	50	5
60	302	195	165	153	156	158	178	210	262	342	455	109.85
55	266	166	141	131	137	142	166	200	256	340	461	110.27
50	232	141	119	113	121	131	157	197	257	344	472	110.76
45	200	118	101	099	109	125	154	199	264	356	490	111.30
40	171	100	088	089	104	123	158	206	284	374	516	111.91
35	146	086	080	085	102	128	168	221	297	401	550	112.56
30	122	071	073	083	104	136	180	239	321	432	587	113.25
25	103	067	073	088	111	151	196	264	353	470	634	113.97
20	087	064	074	096	123	169	225	294	389	514	688	114.76
15	074	064	075	109	138	193	248	329	430	563	745	115.55
10	065	069	093	126	159	220	286	369	476	617	808	116.37
5	059	077	107	165	184	251	323	412	526	775	876	117.21
0	057	089	126	170	212	287	365	460	581	738	948	118.06
5	059	105	149	199	244	227	411	512	640	805	1024	118.51
10	065	125	175	230	281	370	460	567	702	875	1104	119.77
15	074	148	211	265	320	415	516	625	766	947	1185	120.61
20	087	174	238	304	361	465	565	686	833	1042	1268	121.42
25	103	203	271	344	405	515	622	748	901	1098	1354	122.25
30	122	237	309	387	450	568	680	811	971	1174	1439	123.00
35	146	270	350	433	500	624	740	877	1043	1253	1524	123.74
40	171	306	392	479	548	679	800	942	1106	1330	1608	124.45
45	200	346	437	529	601	735	862	1007	1184	1401	1692	125.01
50	232	384	483	577	653	793	923	1073	1255	1482	1774	125.72
55	266	430	529	627	705	850	982	1138	1324	1554	1853	126.27
60	302	473	587	677	758	906	1042	1200	1390	1624	1931	126.77
Ave.	141	173	210	254	296	371	449	544	665	822	1032	118.14

Table III.

Quarter Phase.

Variation of Heating Ratio with Power Factor.

β	Percent Power Factor Lagging.										
	100	95	90	85	80	75	70	65	60	55	50	5
45	183	105	087	082	084	098	119	148	204	279	387	93.69
40	156	088	074	073	078	097	122	160	222	294	412	94.40
35	133	075	066	069	077	101	131	173	235	319	443	95.00
30	111	064	060	068	079	108	142	190	257	347	477	95.71
25	093	057	059	071	086	121	160	213	286	382	520	96.29
20	078	055	061	079	097	138	182	240	319	422	568	97.00
15	070	059	066	094	116	163	208	276	360	471	626	97.75
10	058	060	078	106	132	185	239	309	399	518	680	98.50
5	052	066	091	123	155	213	273	348	445	571	742	99.28
0	051	078	109	147	182	247	312	393	496	629	809	100.05
5	052	092	129	173	211	283	353	440	549	689	878	100.84
10	058	111	154	202	246	323	399	491	607	754	952	101.62
15	070	135	190	238	285	369	454	548	670	825	1030	102.39
20	078	155	211	269	321	410	496	600	727	880	1104	103.16
25	093	183	243	307	362	457	548	657	790	960	1182	103.69
30	111	212	278	346	404	506	602	716	855	1031	1261	104.51
35	133	245	316	389	451	557	657	777	921	1103	1339	105.28
40	156	278	354	429	496	607	712	836	980	1174	1416	105.92
45	183	315	395	476	544	660	769	898	1052	1243	1495	106.67
Ave.	096	123	155	192	227	292	357	438	541	674	854	100.09

Table IV.

Six Phase.

Variation of Heating Ratio with Power Factor.

β	Percent Power Factor Lagging.										
	100	95	90	85	80	75	70	65	60	55	50	5
30	105	060	055	058	064	090	120	159	216	293	404	84.38
25	088	053	054	062	074	103	136	180	243	326	444	85.01
20	074	051	055	069	085	119	157	206	274	364	490	85.67
15	062	050	056	079	099	138	197	235	309	405	539	86.36
10	056	056	072	096	118	174	212	272	351	454	596	87.09
5	050	062	084	112	139	190	243	309	394	504	653	87.81
0	048	072	100	133	164	221	279	350	441	558	716	88.55
5	050	086	120	158	193	256	319	395	492	616	783	89.29
10	056	104	144	196	226	294	362	454	547	678	852	90.03
15	062	112	173	215	257	332	409	493	601	739	921	90.76
20	074	145	197	249	294	375	453	546	660	804	994	91.47
25	088	171	226	284	334	419	512	600	719	870	1068	92.17
30	105	198	259	322	378	466	552	655	780	937	1142	92.72
Ave.	067	091	119	152	183	240	298	369	460	577	735	88.57

Table V.

Twelve Phase.

Variation of Heating Ratio with Power Factor.

β	Percent Power Factor Lagging.										
	I00	95	90	85	80	75	70	65	60	55	50	5
I5	059	046	050	072	089	I26	I60	2I4	28I	369	493	79.54
I0	053	052	067	087	I08	I50	I94	249	32I	4I7	547	80.24
5	047	057	078	I02	I28	I75	224	284	363	464	603	80.94
0	046	068	094	I24	I53	206	259	325	409	5I7	664	8I.65
5	047	08I	II2	I48	I80	239	296	368	457	572	727	82.36
I0	053	098	I25	I75	2I2	276	338	4I5	5II	63I	795	83.08
I5	059	II6	I64	202	243	3I2	384	462	563	69I	86I	83.78
Ave.	050	072	098	I28	I57	2I0	263	329	4I3	52I	668	8I.65

Table VI.

Infinite Phase.

Variation of Heating Ratio with Power Factor.

β	Percent Power Factor Lagging.										
	I00	95	90	85	80	75	70	65	60	55	50	5
Ave.	047	069	094	II5	I53	205	258	323	405	5I3	657	85.30

Table VII.

Comparison of Heating Ratios.

Variation with Phase and Power Factor; 0 to ∞; I00% to 50%.

"n"	Power Factor Percent Lagging.										
	I00	95	90	85	80	75	70	65	60	55	50	5
I	∞	–	∞	–	∞	–	∞	–	∞	–	∞	–
2	345	400	460	535	608	735	865	I025	I230	I495	I855	I99.3
3	I43	I73	2II	253	296	372	445	545	666	82I	I035	II7.8
4	095	I22	I53	I90	227	290	356	436	539	670	850	99.7
5	08I	I07	I35	I7I	205	265	327	403	500	624	795	94.2
6	067	09I	II8	I5I	I83	240	299	370	46I	577	739	88.4
7	062	096	II2	I45	I76	23I	289	358	446	555	7I8	86.5
8	058	083	I08	I40	I7I	226	282	35I	439	550	705	85.3
9	055	078	I03	I45	I65	2I9	275	34I	428	538	690	83.8
I0	053	076	I0I	I32	I62	2I5	270	336	422	53I	68I	82.8
50	050	072	097	I28	I57	2I0	264	330	4I4	52I	670	8I.8
∞	047	069	093	I24	I53	205	258	323	405	5II	657	80.4

Table VIII.

Variation of Permissible Rating with Power Factor.

"n"	Percent Power Factor Lagging										
-	I00	95	90	85	80	75	70	65	60	55	50	5
2	I000	925	825	804	754	686	625	57I	530	480	427	04I6
3	I000	90I	820	745	690	6I5	560	507	460	4I4	370	0326
4	I000	883	790	707	648	573	5I8	467	420	377	335	0296
6	I000	850	736	650	598	522	460	4I0	369	328	29I	0256
∞	I000	828	7I0	620	560	484	430	385	344	306	270	0240

Table IX.

Value of Lag Angles for Various Power Factors.

	Percent Power Factor.											
	I00	95	90	85	80	75	70	65	60	55	50	5
Deg.	0	I8	25	3I	35	4I	45	49	53	56	60	87
Min.	0	I2	50	44	54	25	34	27	8	38	0	8

Table X.

Variation of Maximum Heating Ratio with Power Factor.

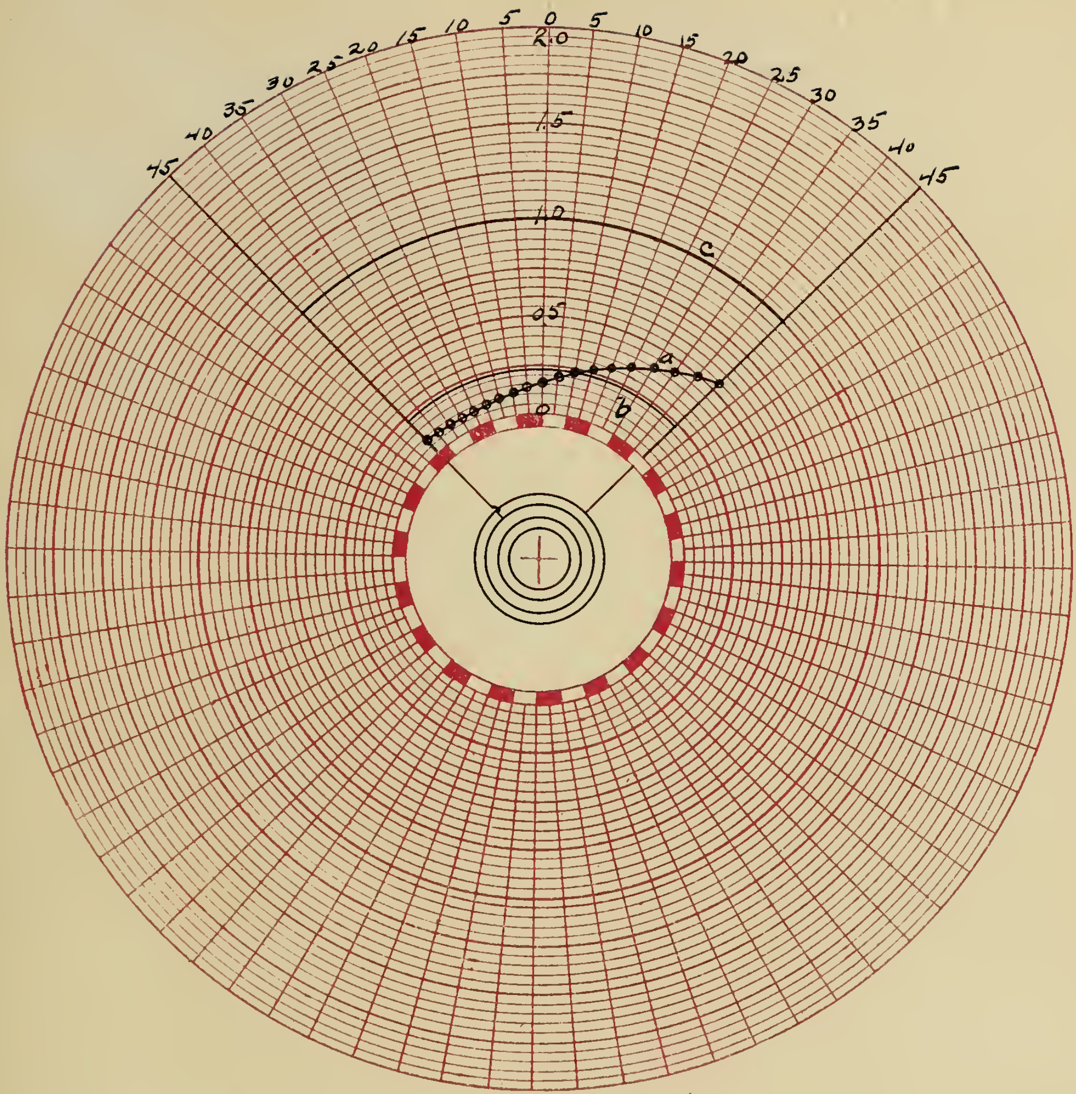
"n"	Percent Power Factor Lagging.										
-	I00	95	90	85	80	75	70	65	60	55	50	5
2	750	I0I3	II74	I335	I47I	I699	I9I8	2I73	2480	2864	3357	2I2.42
3	302	473	587	677	758	906	I042	I200	I390	I624	I93I	I26.77
4	I83	3I5	395	476	544	660	769	898	I052	I243	I495	I06.67
6	I05	I98	259	322	378	466	552	655	780	937	II42	92.72
I2	059	II6	I64	202	243	3I2	384	462	563	69I	86I	8I.65
∞	047	069	094	II5	I53	205	258	323	405	5I3	657	85.35

Table XI.

Variation of Voltage Ratio with Phase Rating

	Values of "n".					
	2	3	4	6	I2	∞
Ratio	707I	6I30	5000	3530	I822	0

C U R V E S.



Sample Curve.

Distribution of Heating.

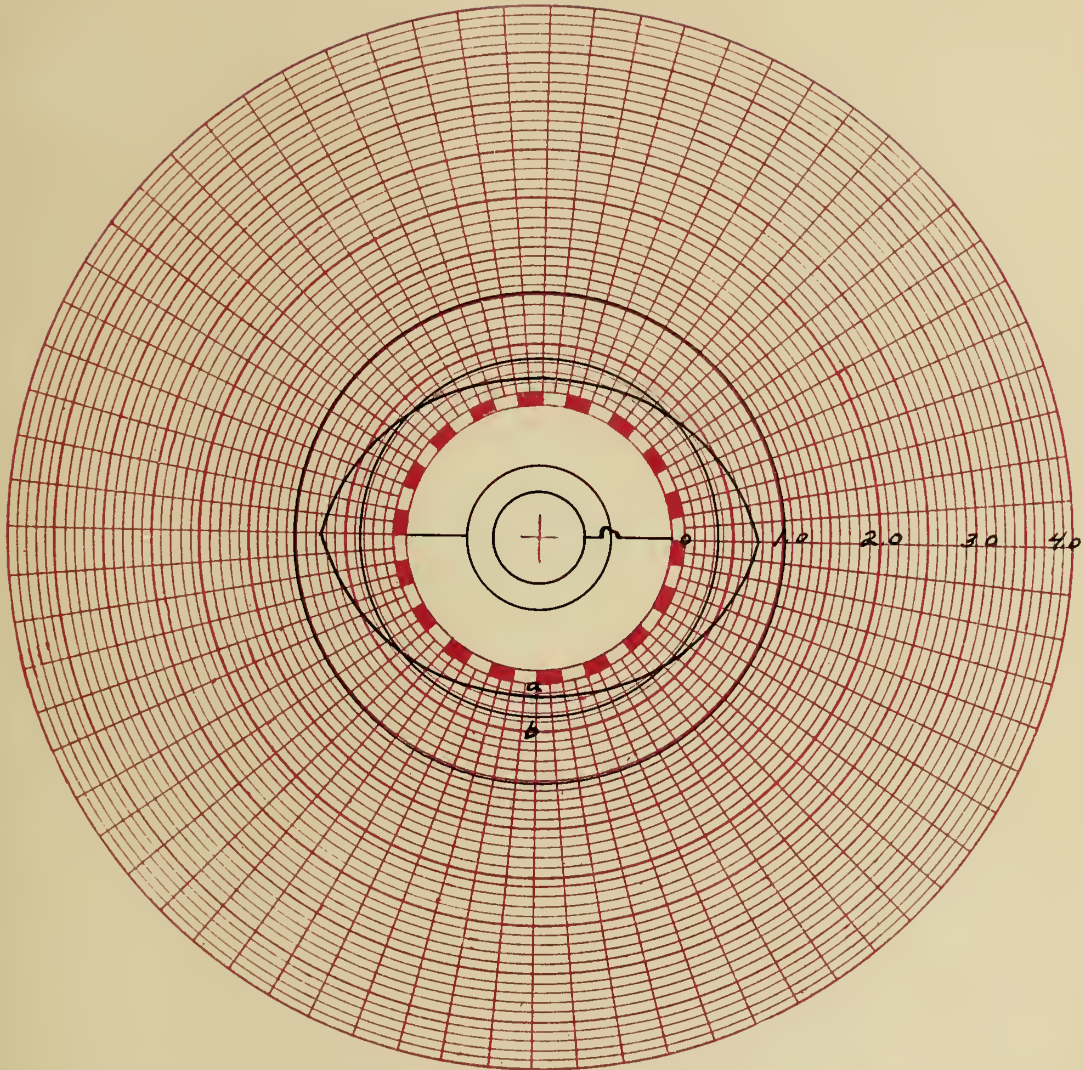
Quarter Phase.

"n" 4. P.F. 80%

a--Distribution.

b--Average.

c--Equivalent Heating of Direct Line Current.



Distribution of Heating.

Single Phase.

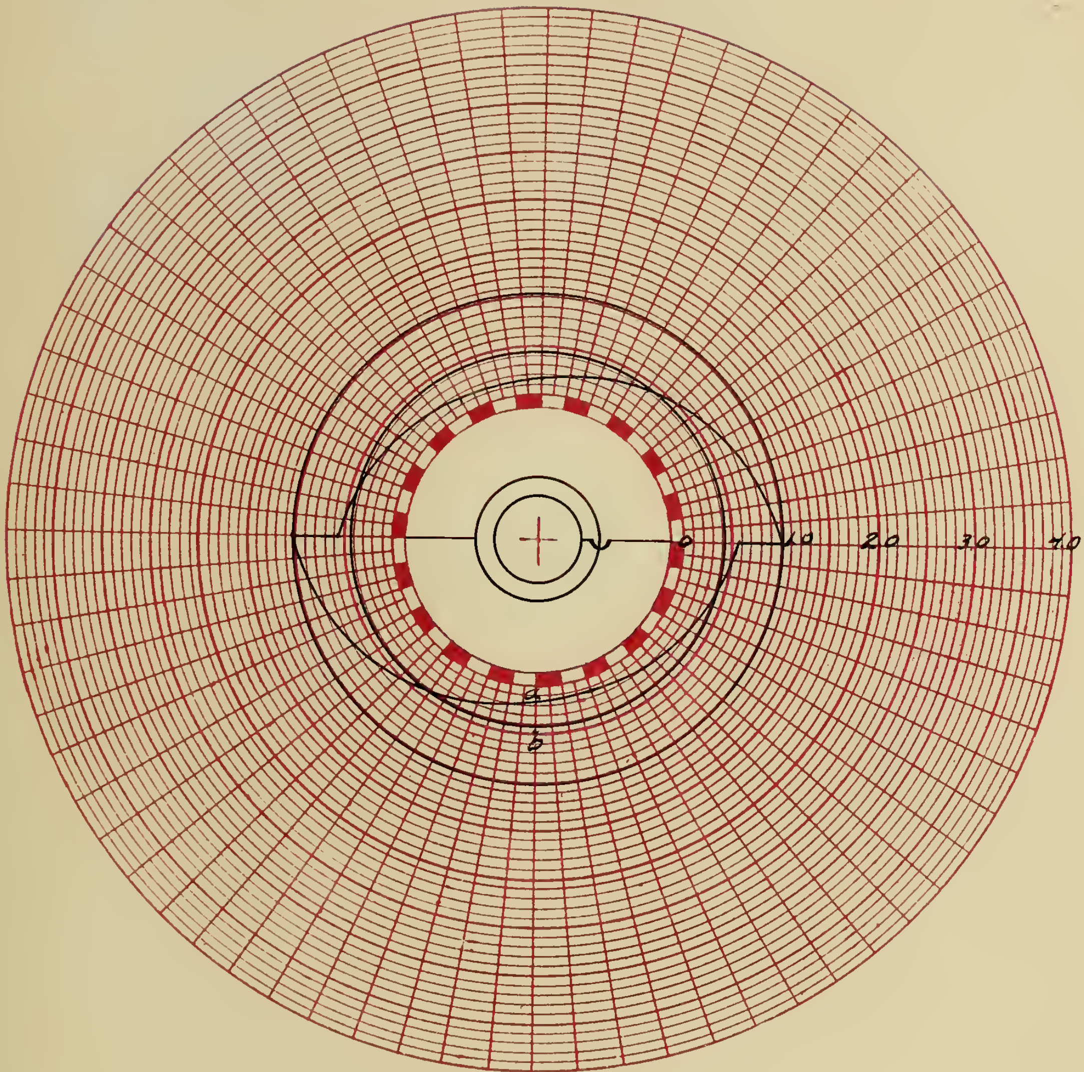
"n" 2 P.F. 100%

a--Distribution.

Max. .750 Min. .115

b--Average.

.345



Distribution of Heating.

Single Phase.

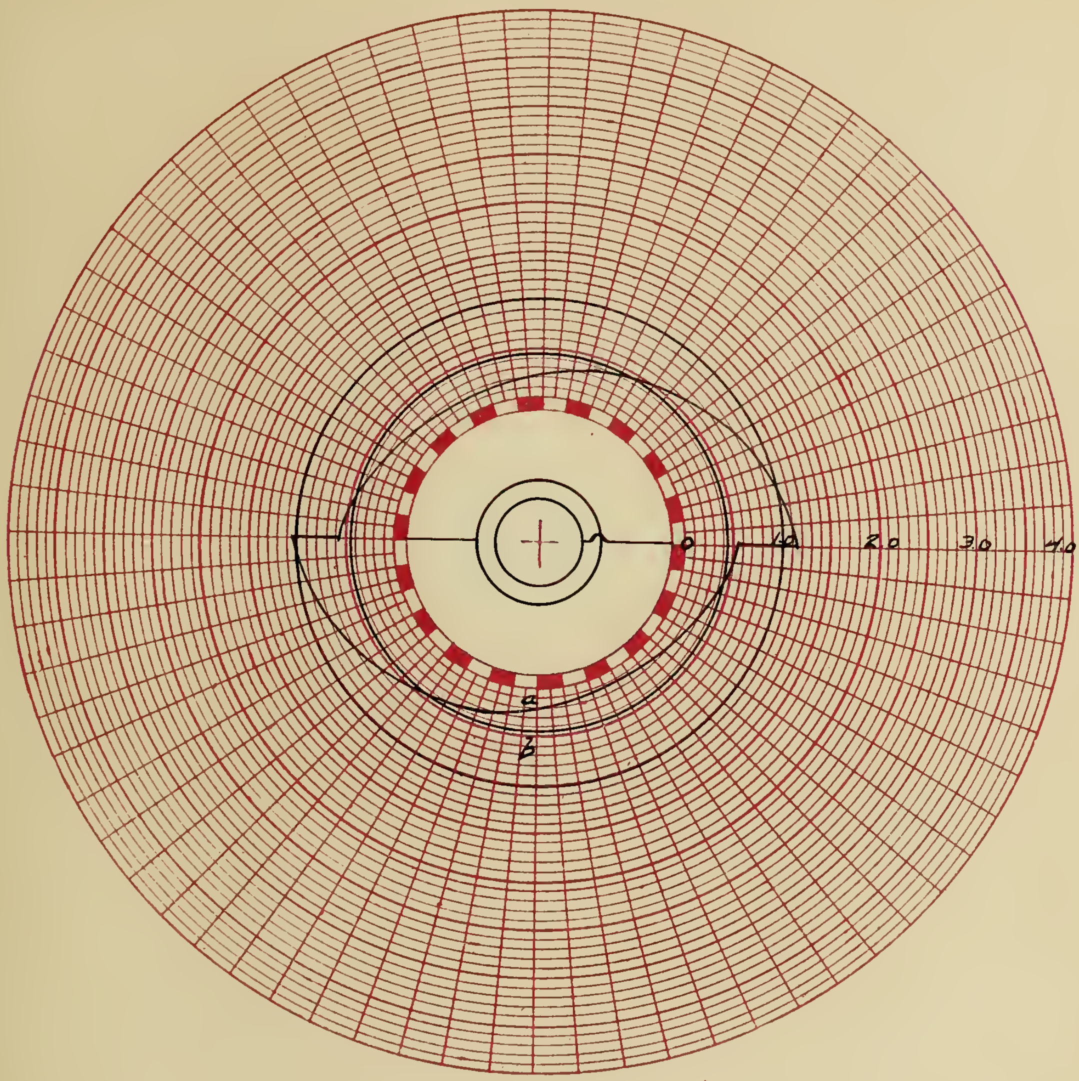
"n" 2. P.F. 95%

a--Distribution.

Max. I.0I3 Min. .I35

b--Average.

.435



Distribution of Heating.

Single Phase.

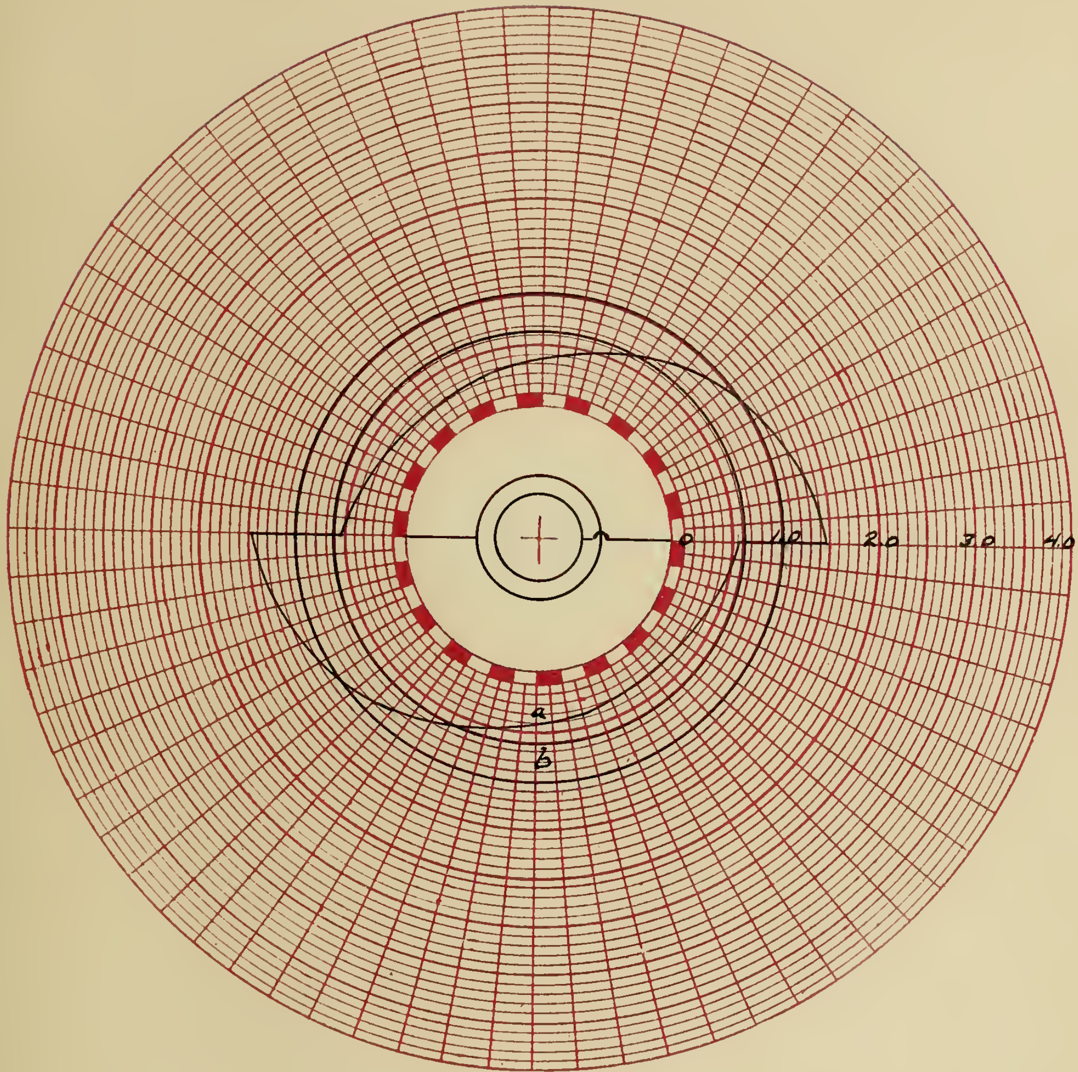
"n" 2. P.F. 90%

a--Distribution.

Max. I.I74 Min. .I6I

b--Average.

,462



Distribution of Heating.

Single Phase.

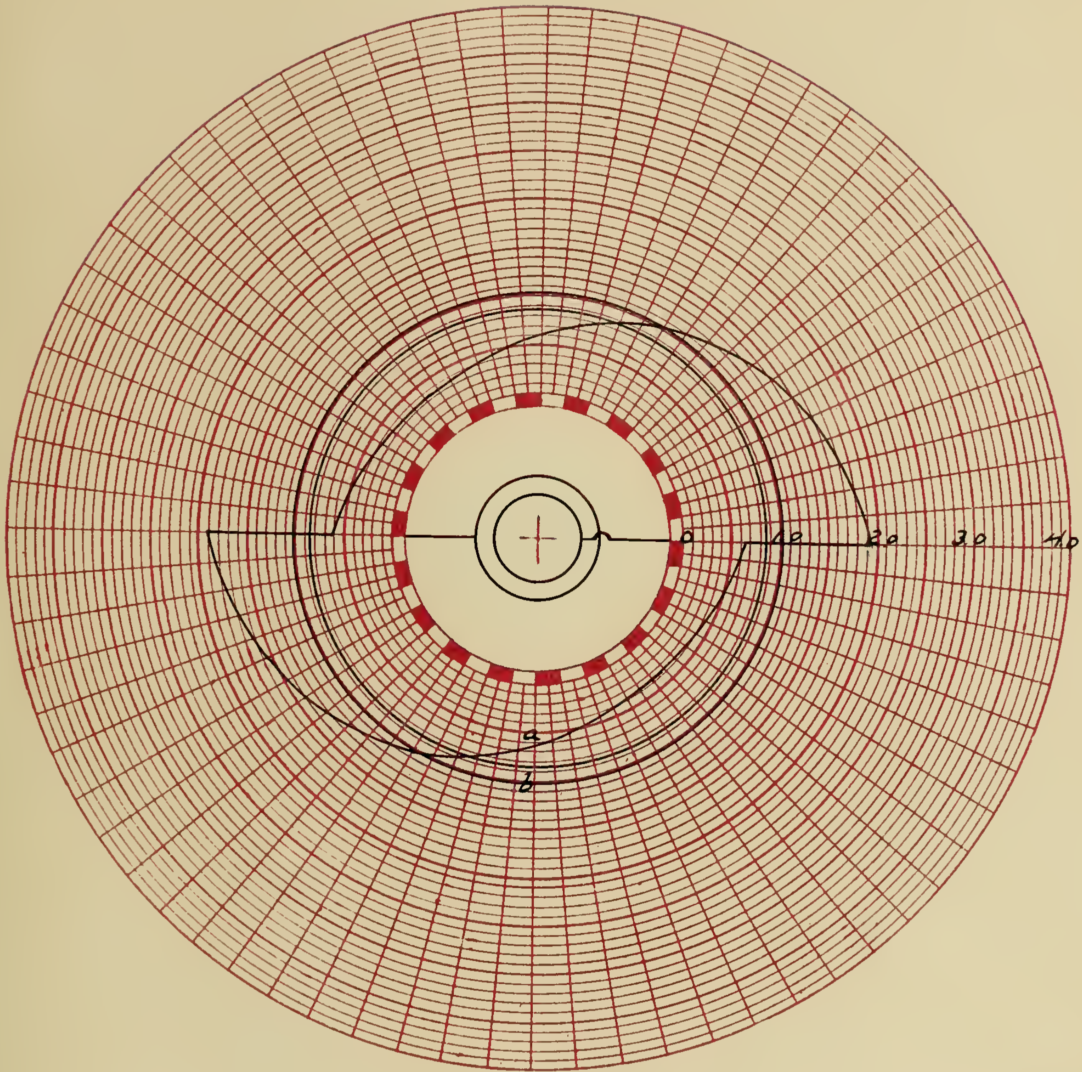
"n" 2. P.F. 80%

a--Distribution.

Max. I.47I Min. .228

b--Average.

.607



Distribution of Heating.

Single Phase.

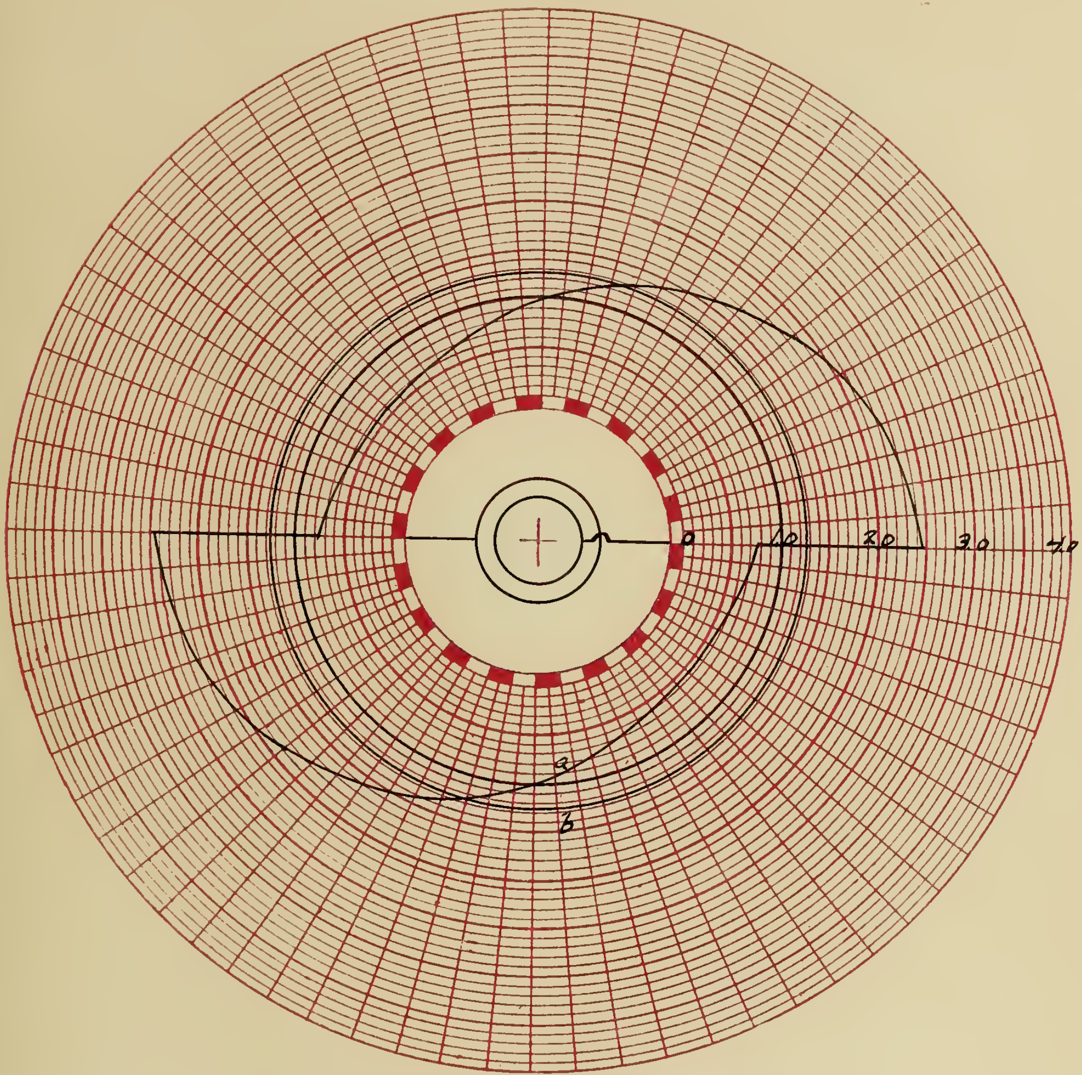
"n" 2. P.F. 70%

a--Distribution.

Max. I.9I8 Min. .36I

b--Average.

.865



Distribution of Heating.

Single Phase.

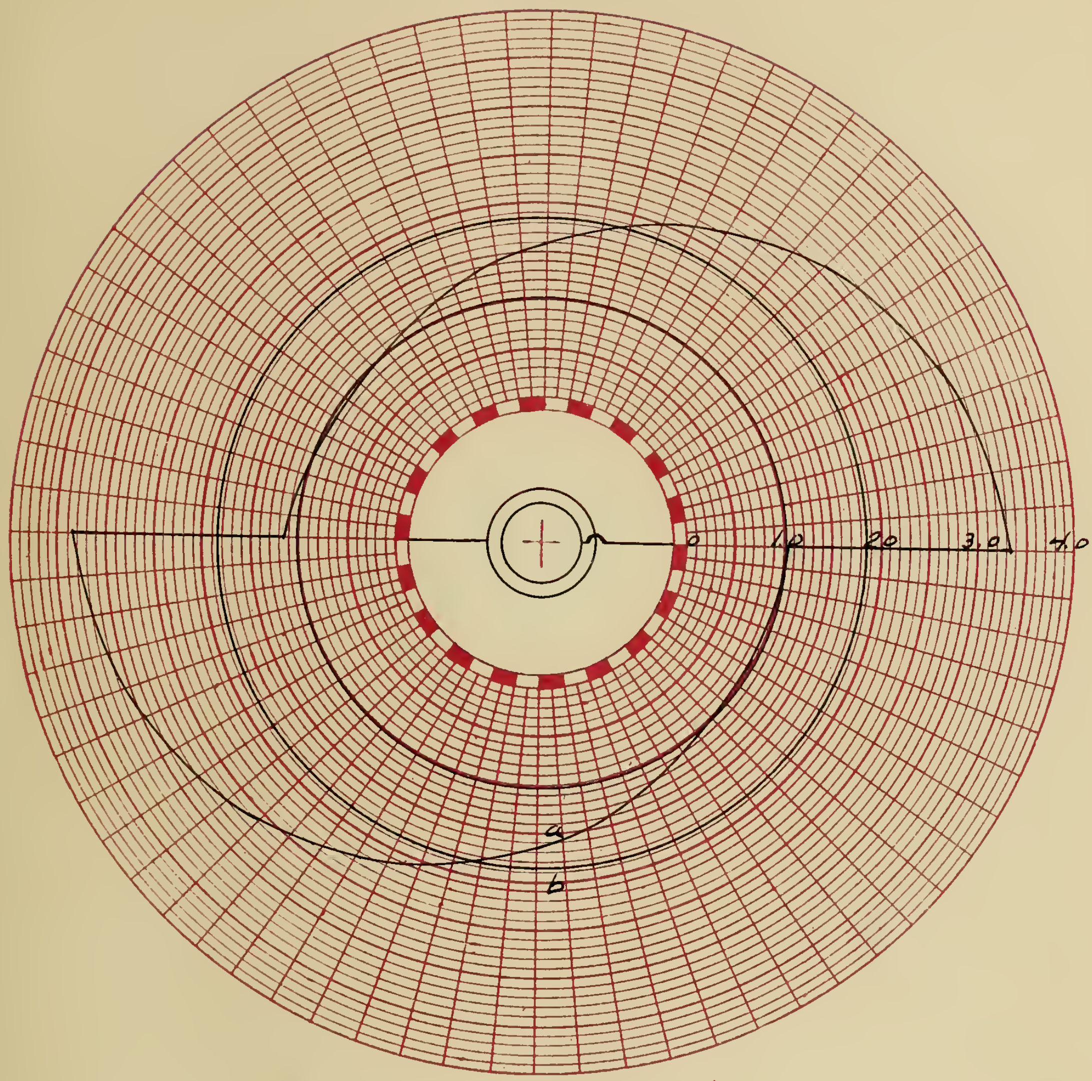
"n" 2 P.F. 60%

a--Distribution.

Max. 2.480 Min. .578

b--Average.

I.230



Distribution of Heating.

Single Phase.

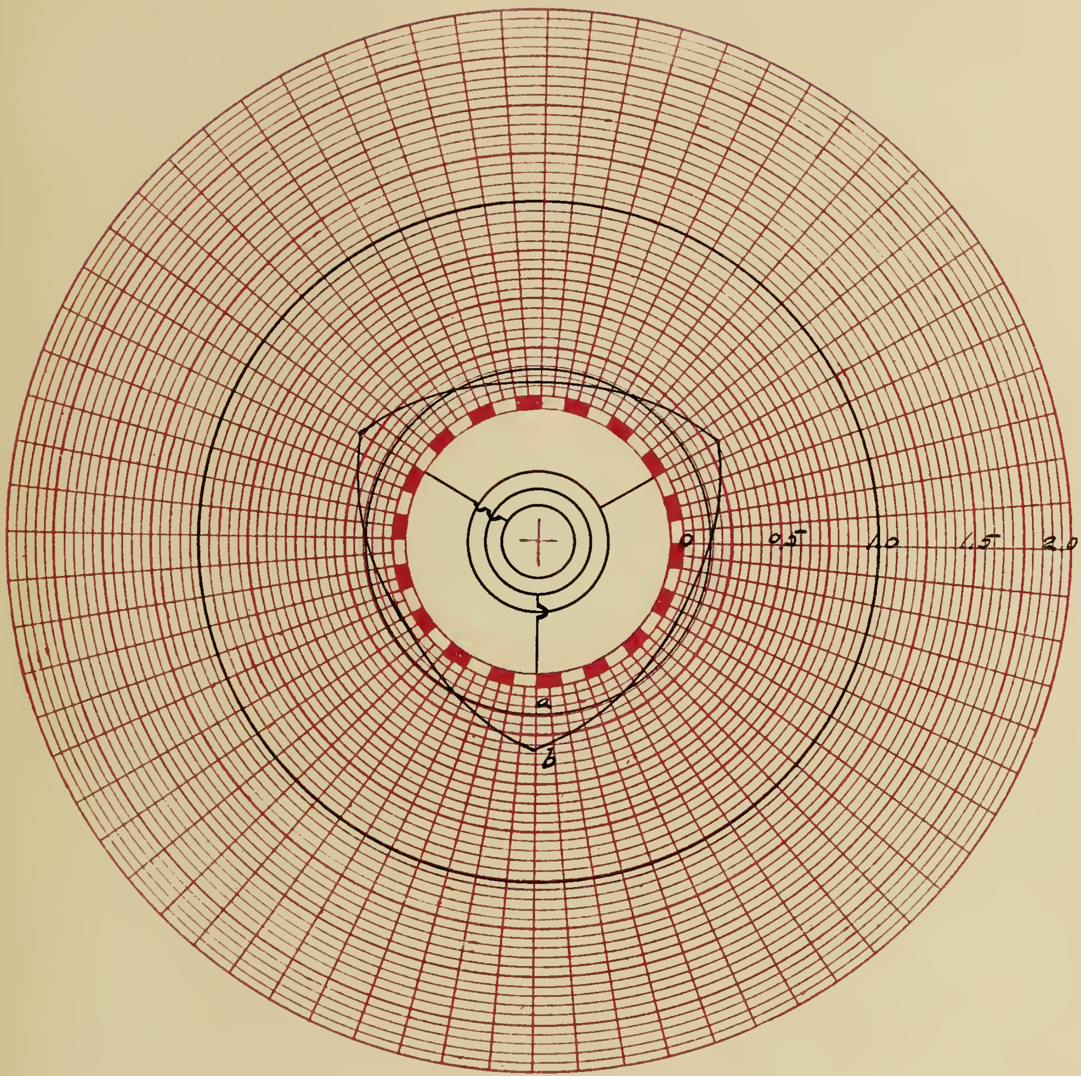
"n" 2 P.F. 50%

a--Distribution.

Max. 3.357 Min. .970

b---Average.

1.845



Distribution of Heating.

Three Phase.

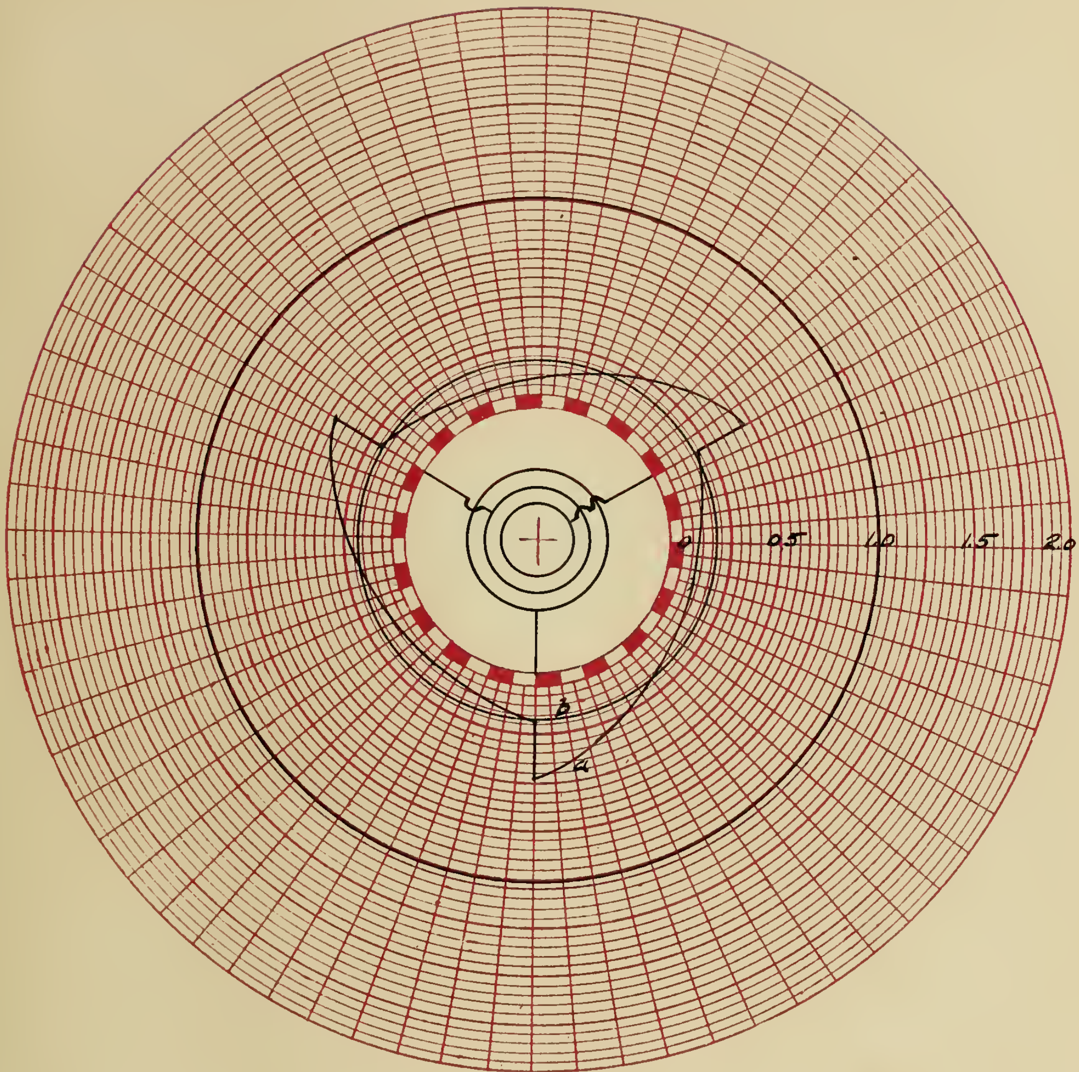
"n" 3. P.F. 100%

b--Distribution.

Max. .302 Min. .057

a--Average.

.141



Distribution of Heating.

Three Phase.

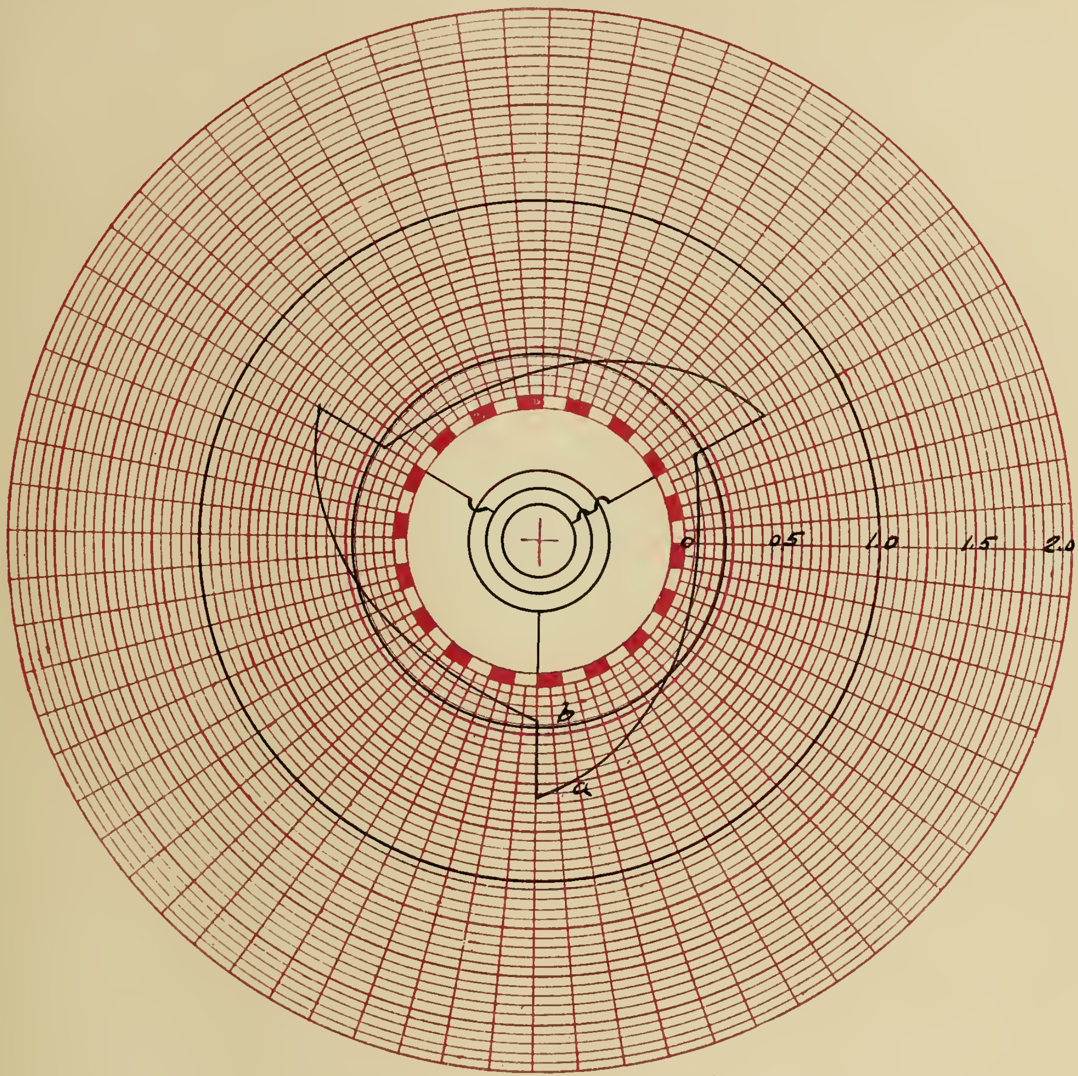
"n" 3. P.F. 95%

a--Distribution.

Max. .473 Min. .064

b--Average.

.173



Distribution of Heating.

Three Phase.

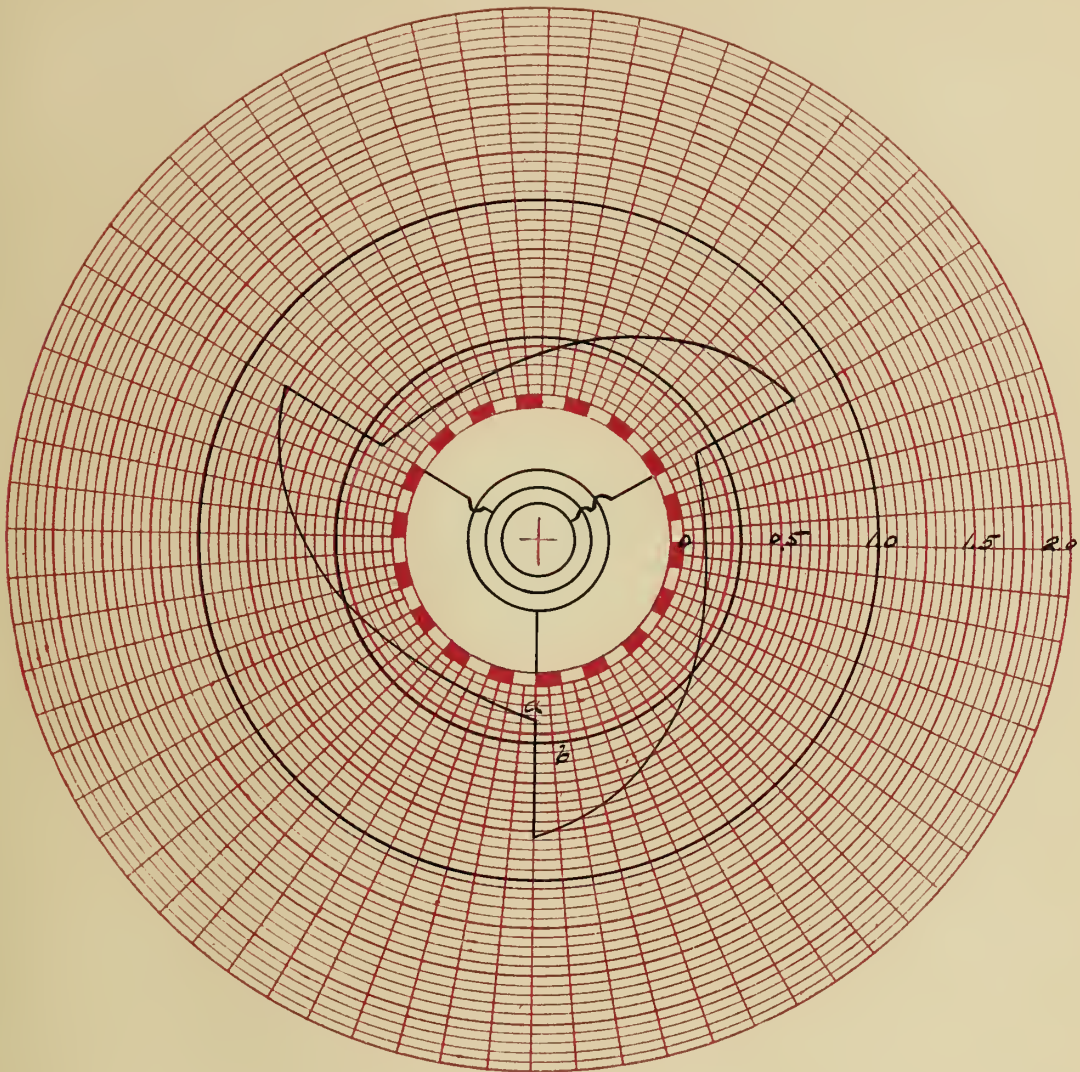
"n" 3. P.F. 90%

a--Distribution.

Max. .587 Min. .073

b--Average.

.210



Distribution of Heating.

Three Phase.

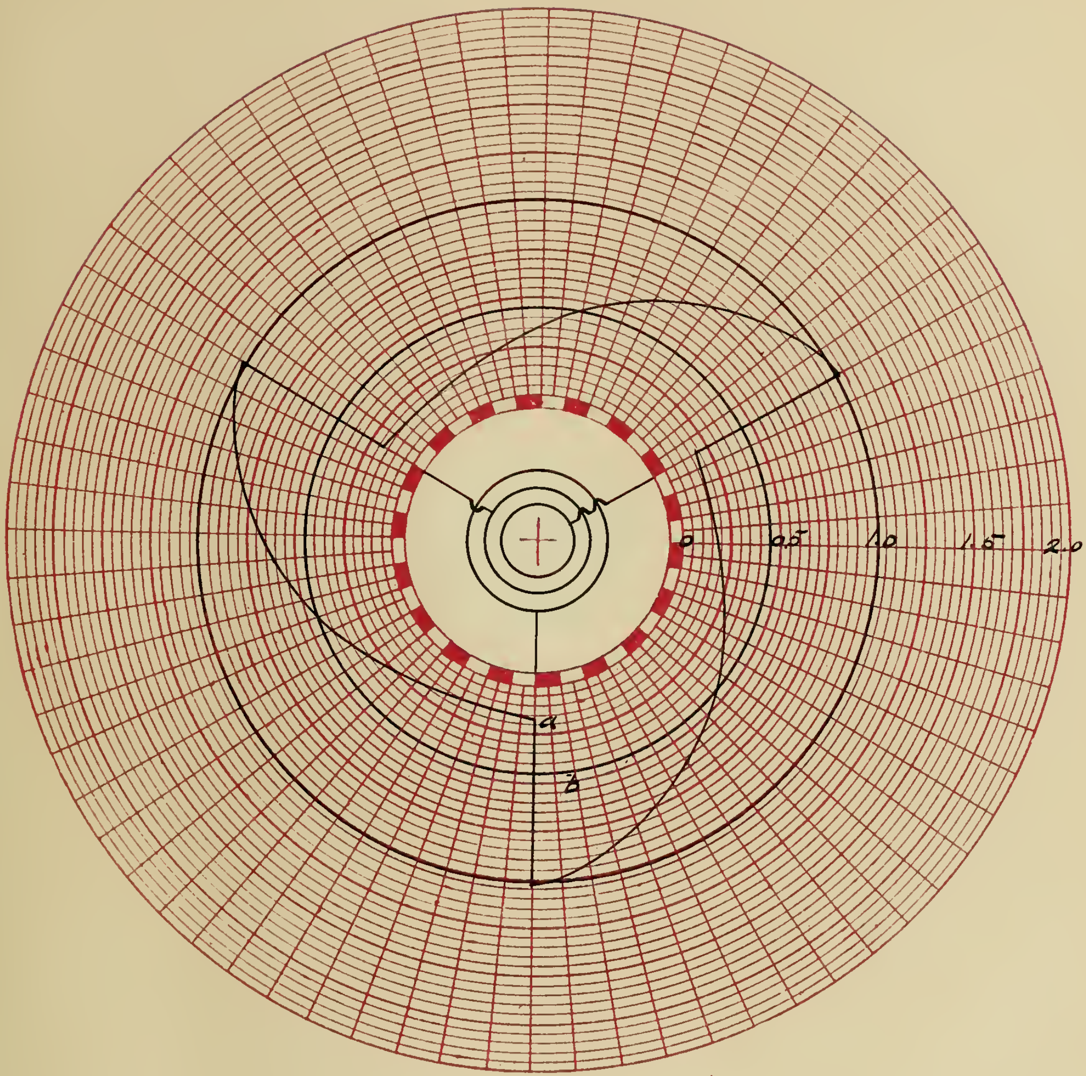
"n" 3. P.F. 80%

a--Distribution.

Max. .758 Min. .102

b--Average.

.296



Distribution of Heating.

Three Phase.

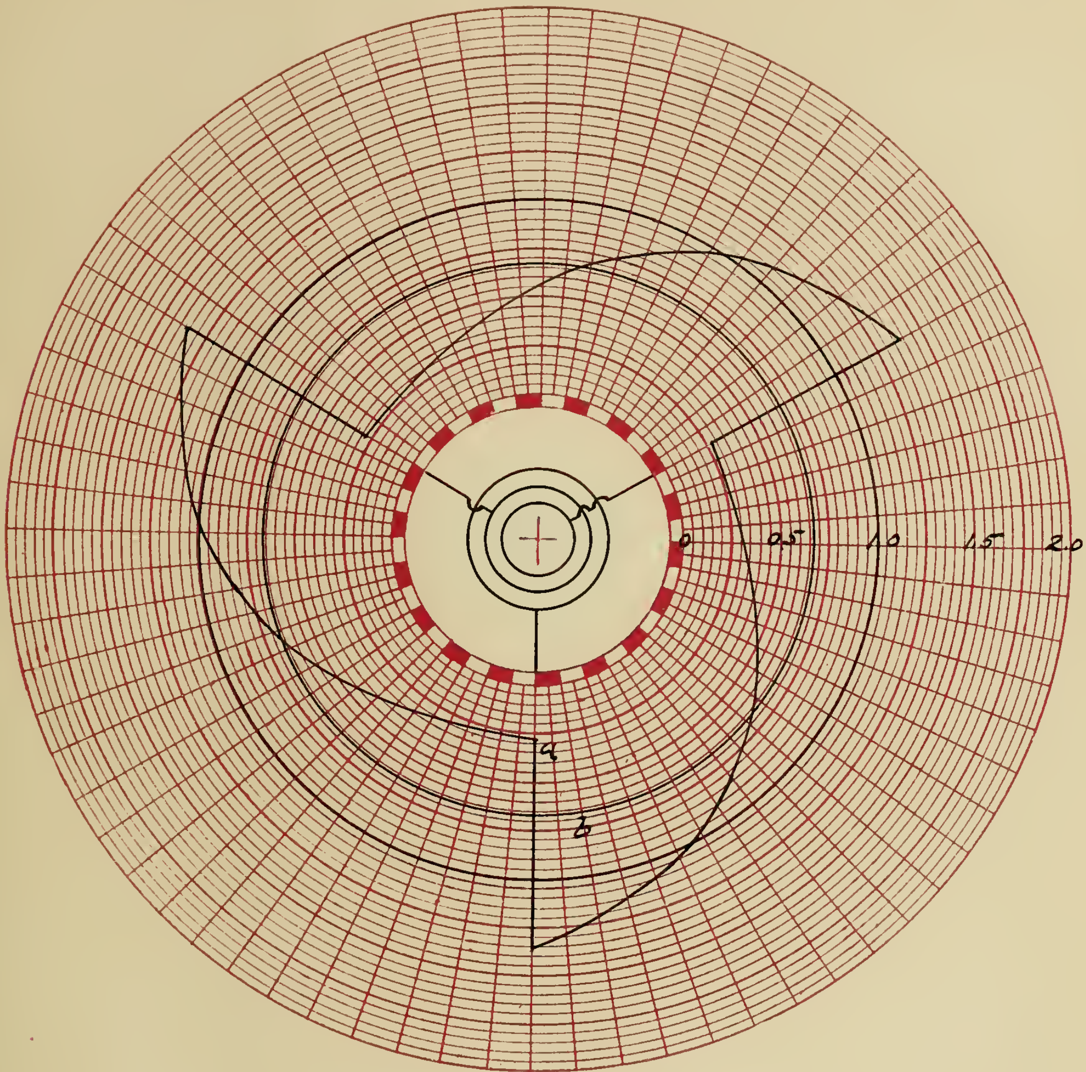
"n" 3. P.F. 70%

a--Distribution.

Max. 1.042 Min. .154

b--Average.

.448



Distribution of Heating.

Three Phase.

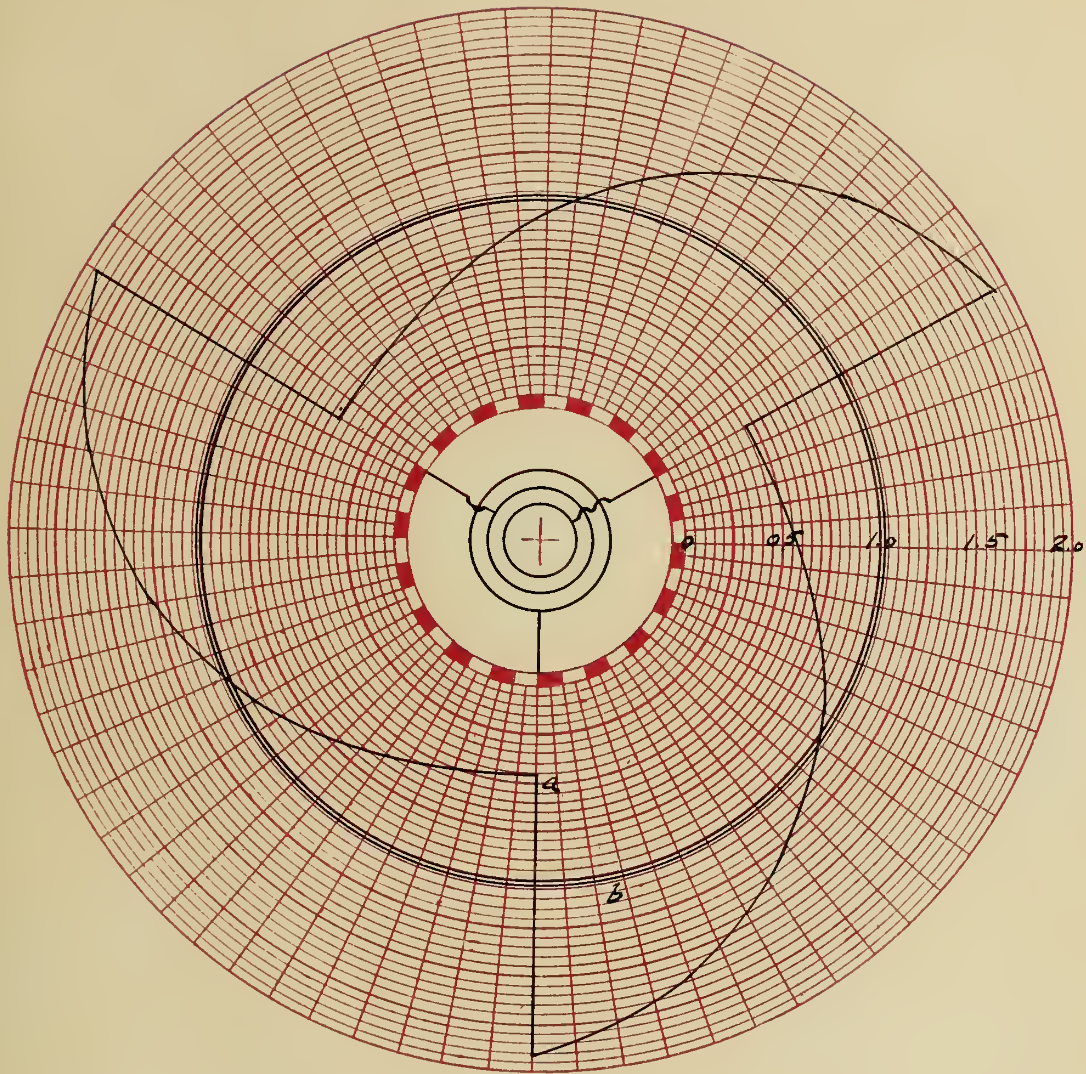
"n" 3. P.F. 60%

a--Distribution.

Max. I.390 Min. .256

b--Average.

.665



Distribution of Heating.

Three Phase.

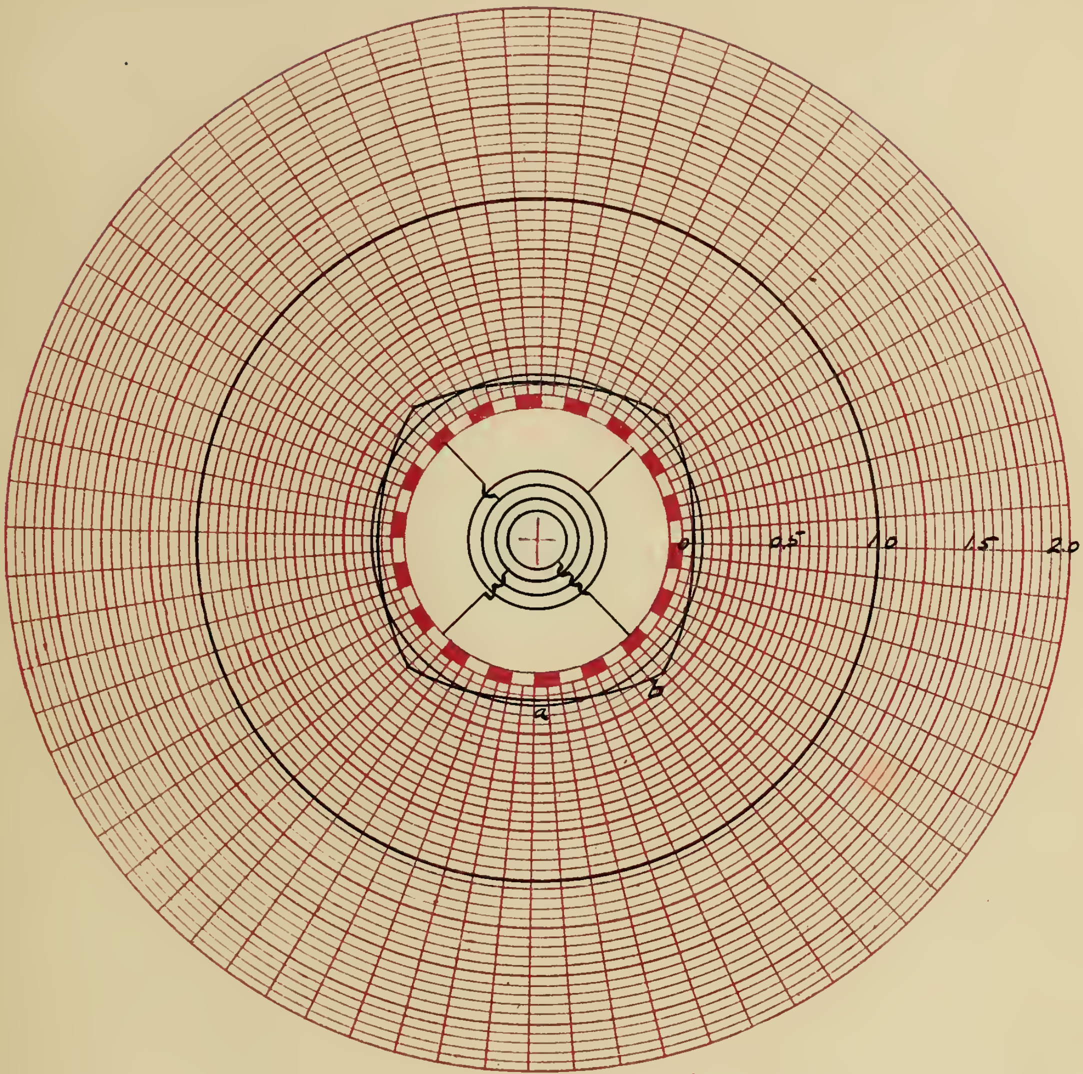
"n" 3. P.F. 50%

a--Distribution.

Max. I.93I Min. .455

b--Average.

I.032



Distribution of Heating.

Quarter Phase.

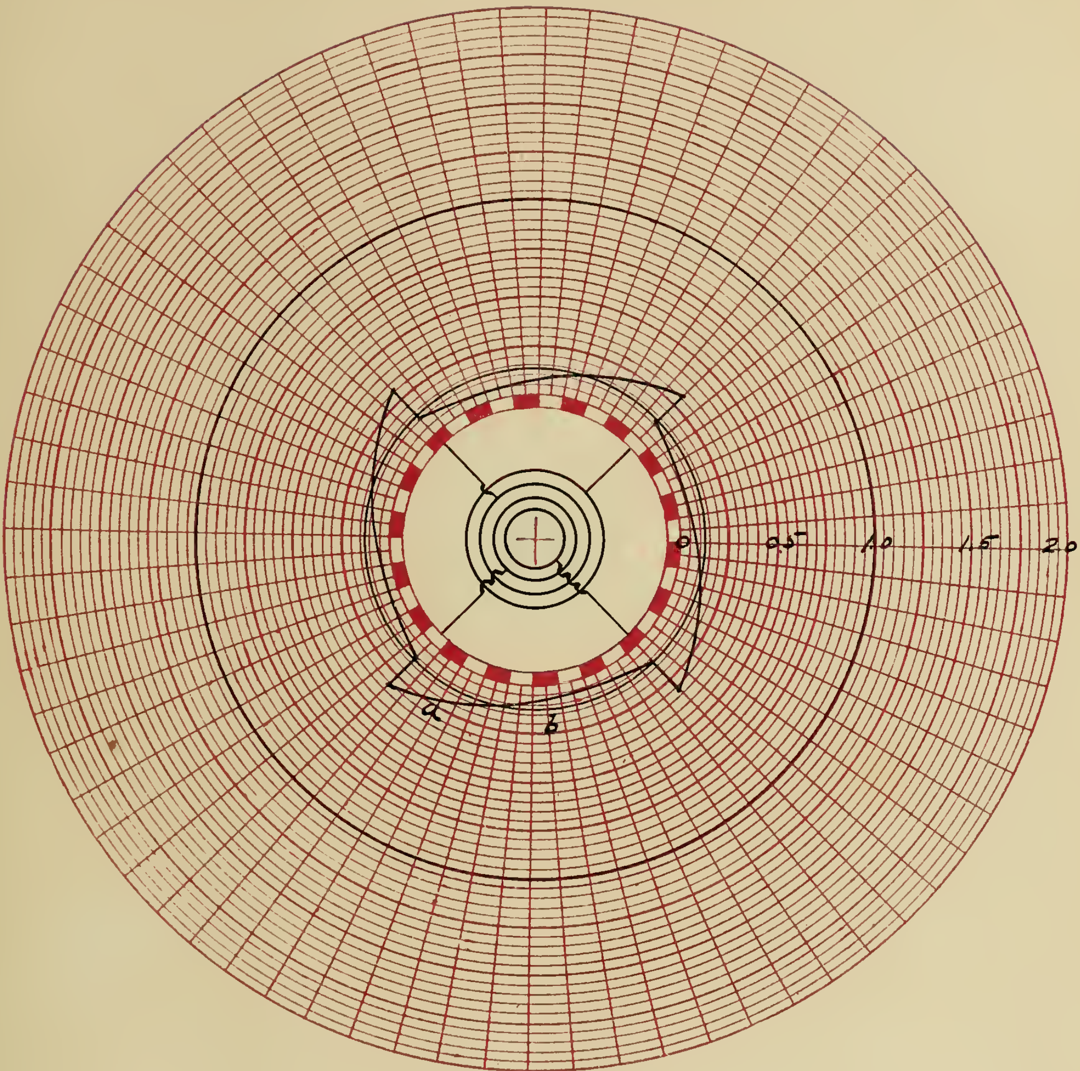
"n" 4. P.F.I00%

b--Distribution.

Max. .I83 Min. .05I

a--Average.

.096



Distribution of Heating.

Quarter Phase

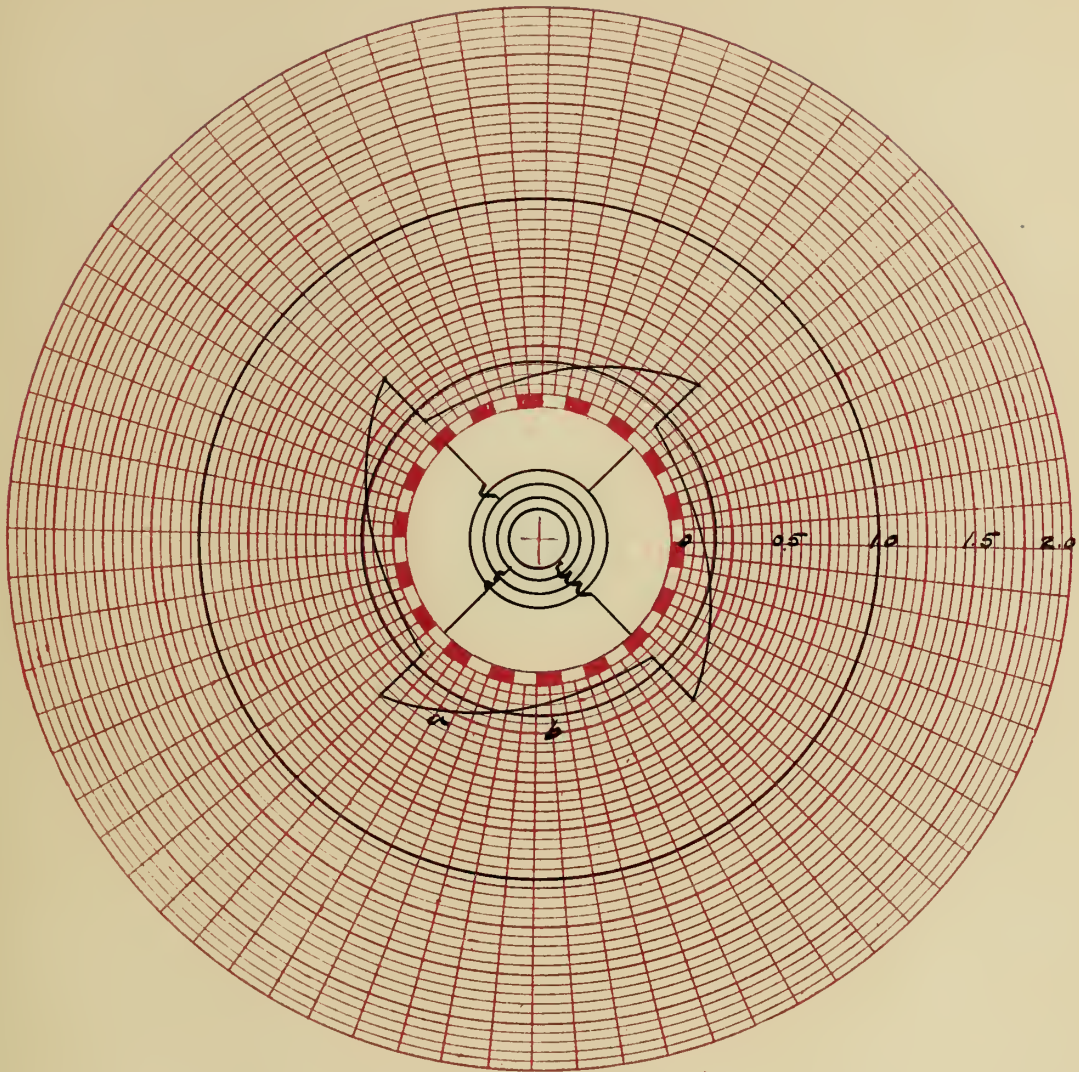
"n" 4 P.F. 95%

a--Distribution.

Max. .315 Min. .055

b--Average.

.123



Distribution of Heating.

Quarter Phase.

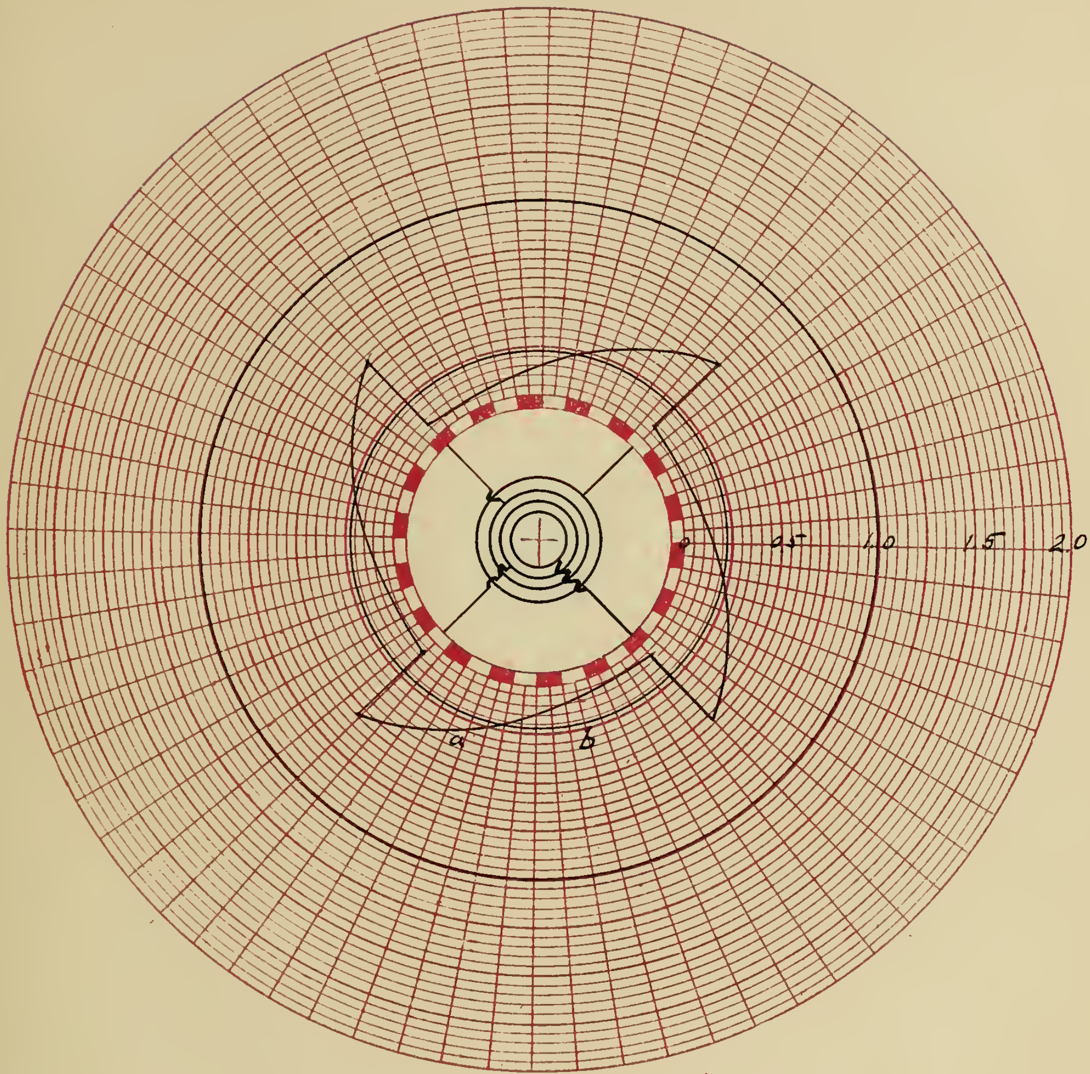
"n" 4. P.F. 90%

a--Distribution.

Max. .395 Min. .059

b--Average.

.I55



Distribution of Heating.

Quarter Phase.

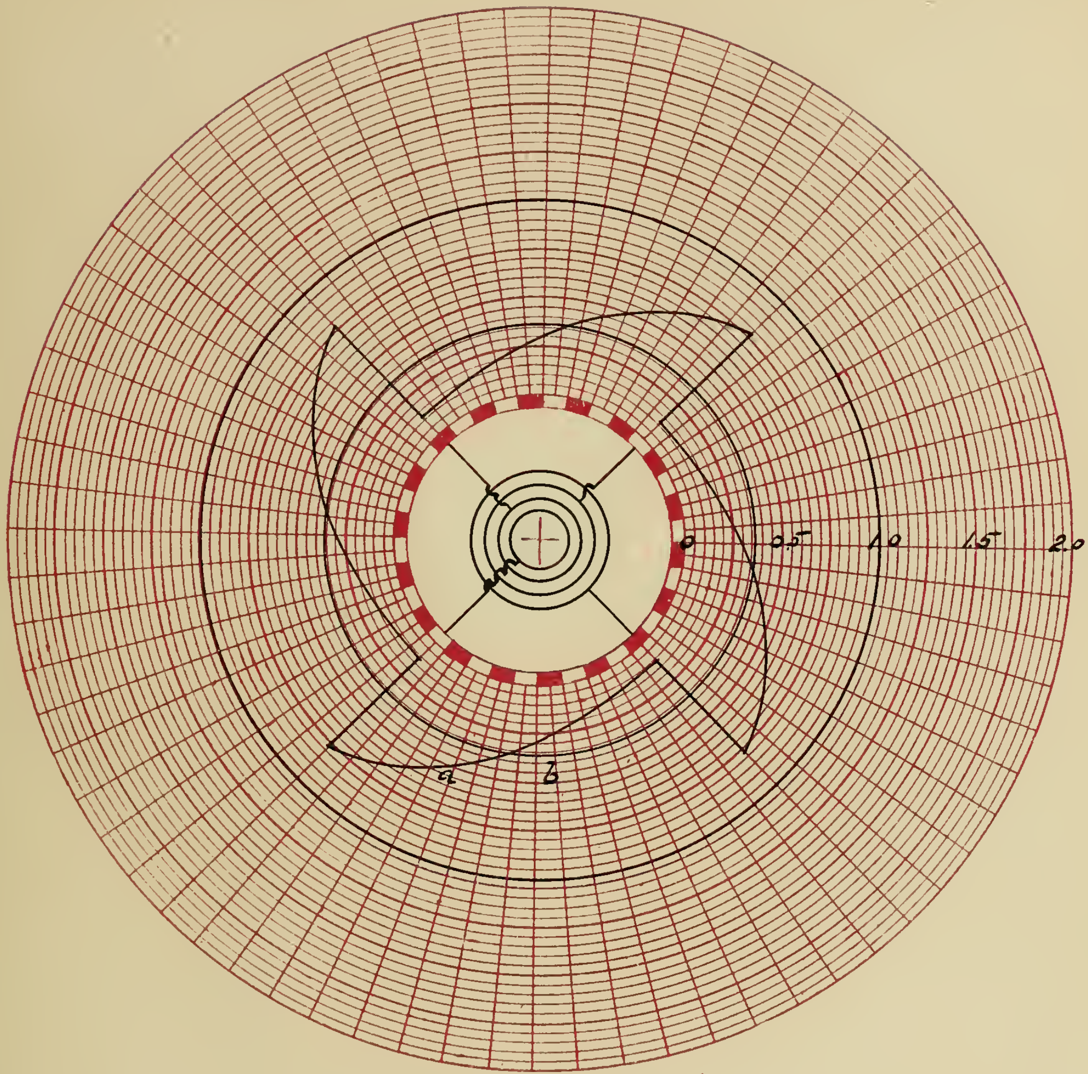
"n" 4. P.F. 80%

a--Distribution.

Max. .544 Min. .077

b--Average.

.227



Distribution of Heating.

Quarter Phase.

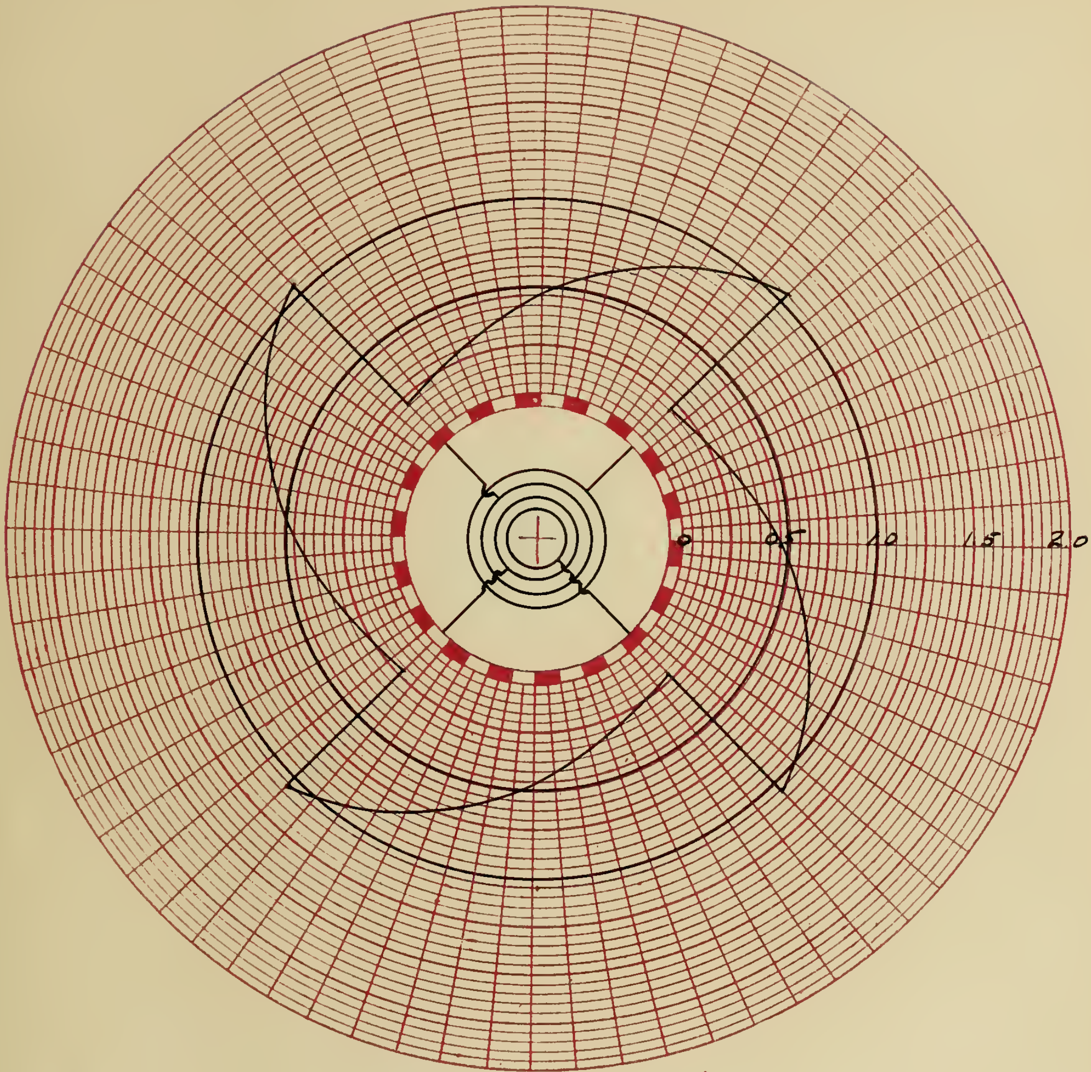
"n" 4 P.F. 70%

a--Distribution.

Max. .769 Min. .II9

b--Average.

.357



Distribution of Heating.

Quarter Phase.

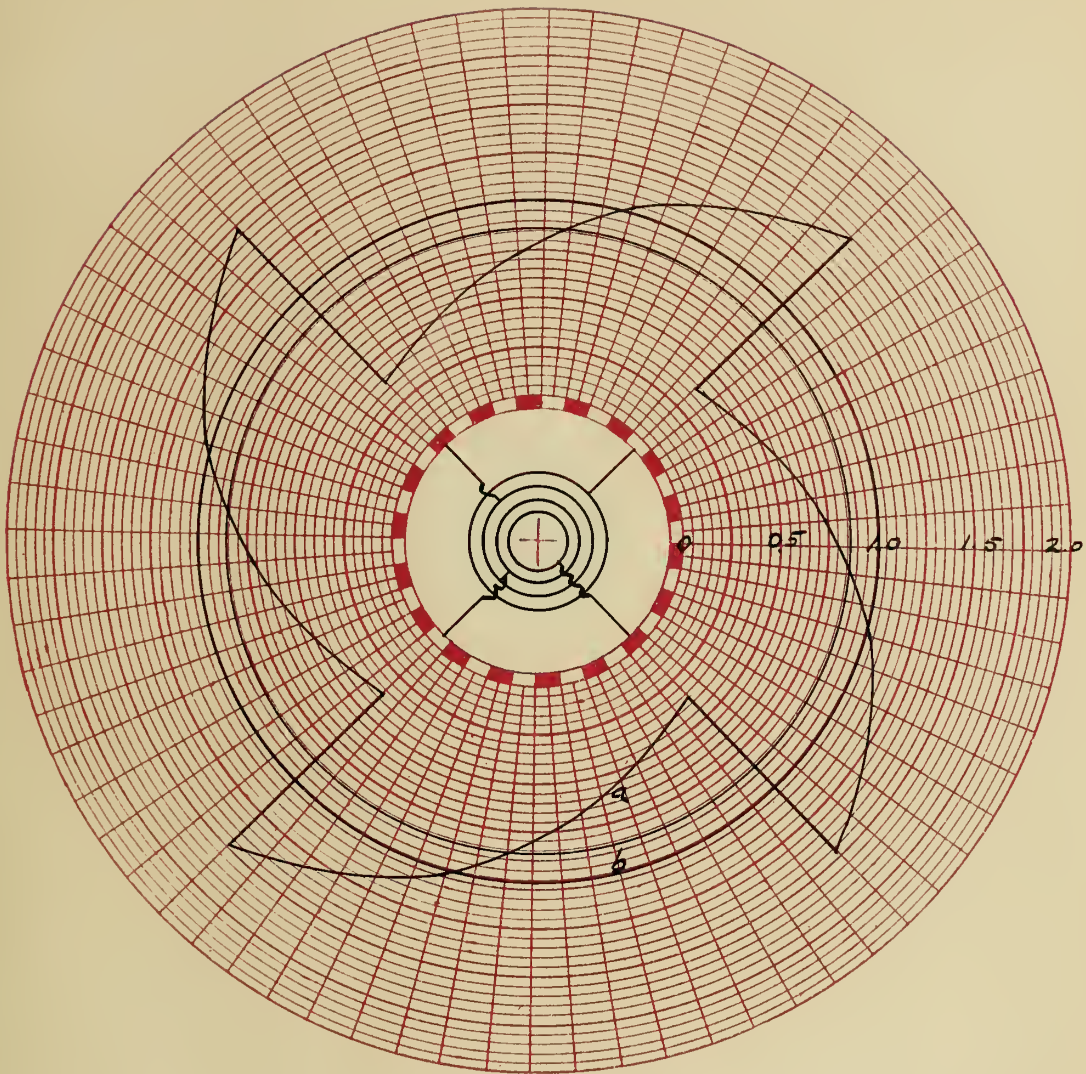
"n" 4. P.F. 60%

a--Distribution.

Max. I.052 Min. .204

b--Average.

.54I



Distribution of Heating.

Quarter Phase

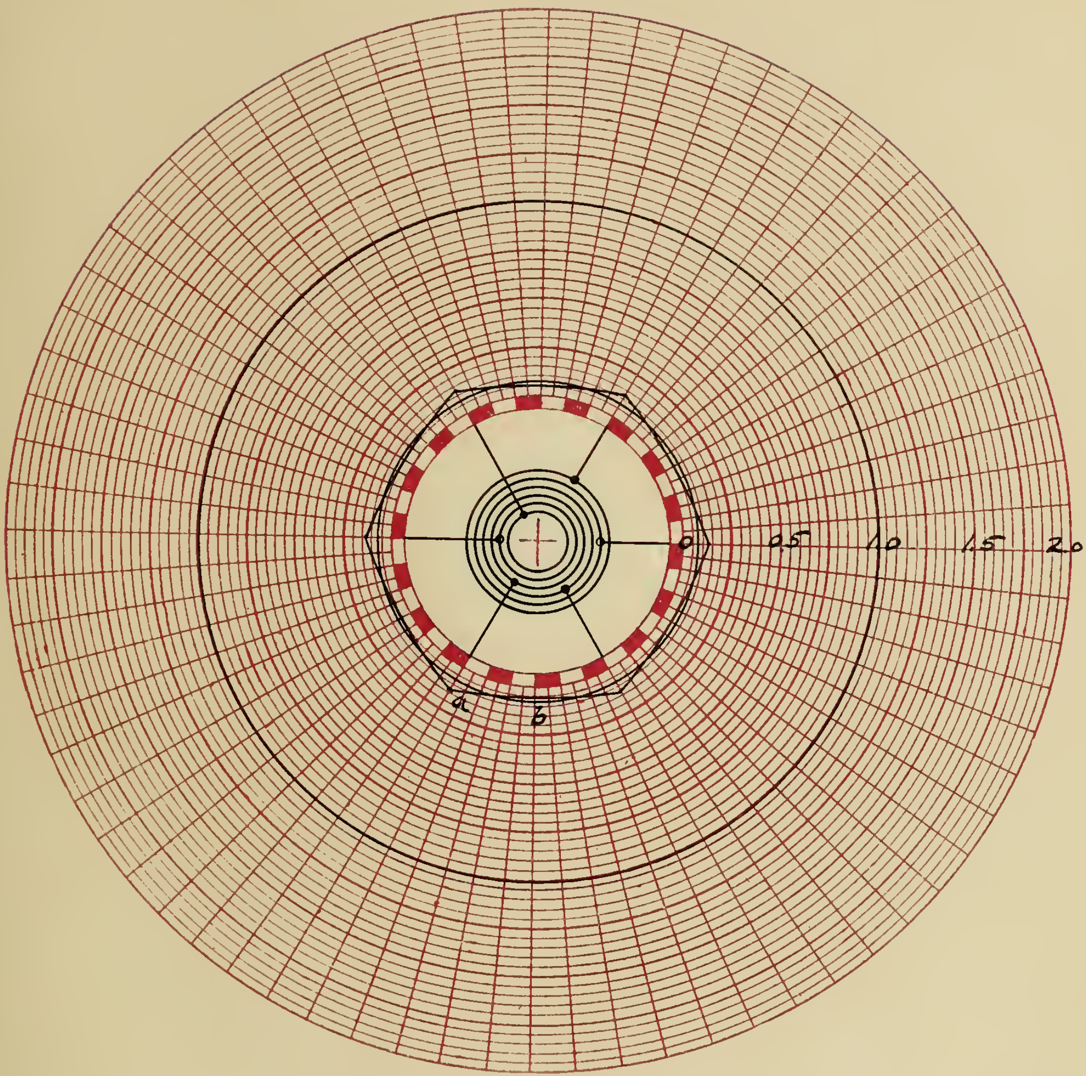
"n" 4. P.F. 50%

a--Distribution.

Max. I.495 Min. .387

b--Average.

.854



Distribution of Heating.

Six Phase.

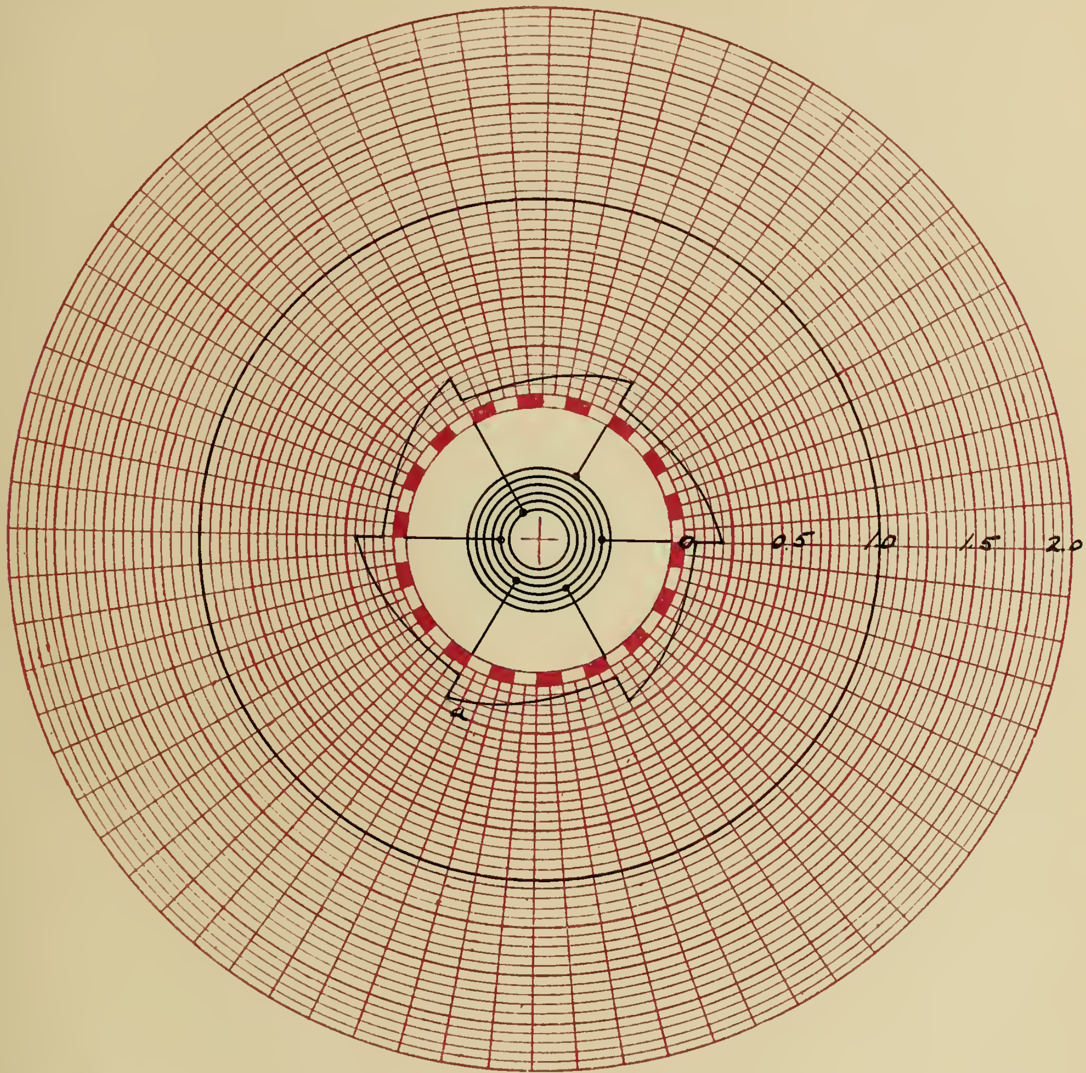
"n" 6. P.F. 100%

a--Distribution

Max. .105 Min. .048

b--Average.

.067



Distribution of Heating.

Six Phase.

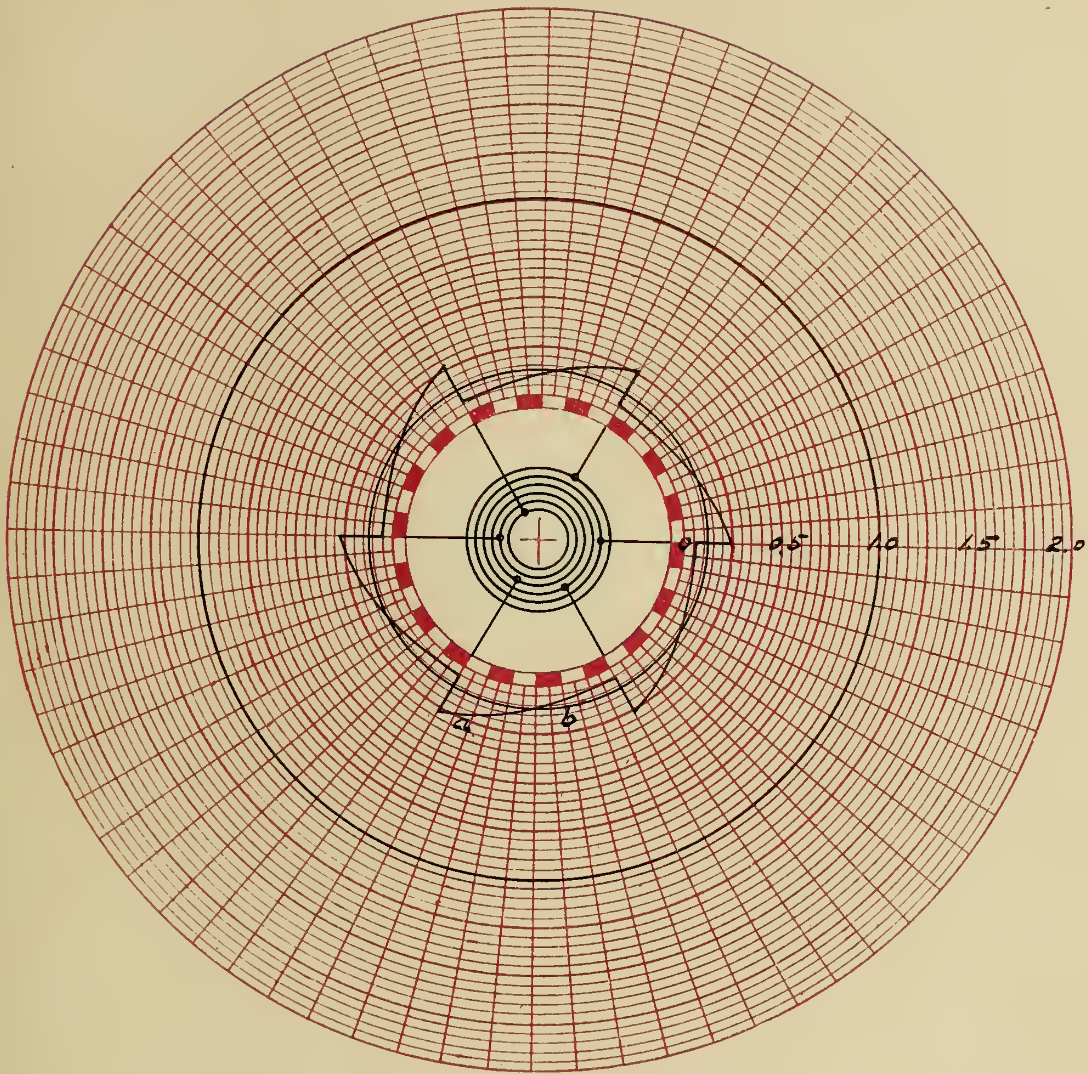
"n" 6. P.F. 95%

a--Distribution.

Max. .I98 Min. .050

b--Average.

.09I



Distribution of Heating.

Six Phase.

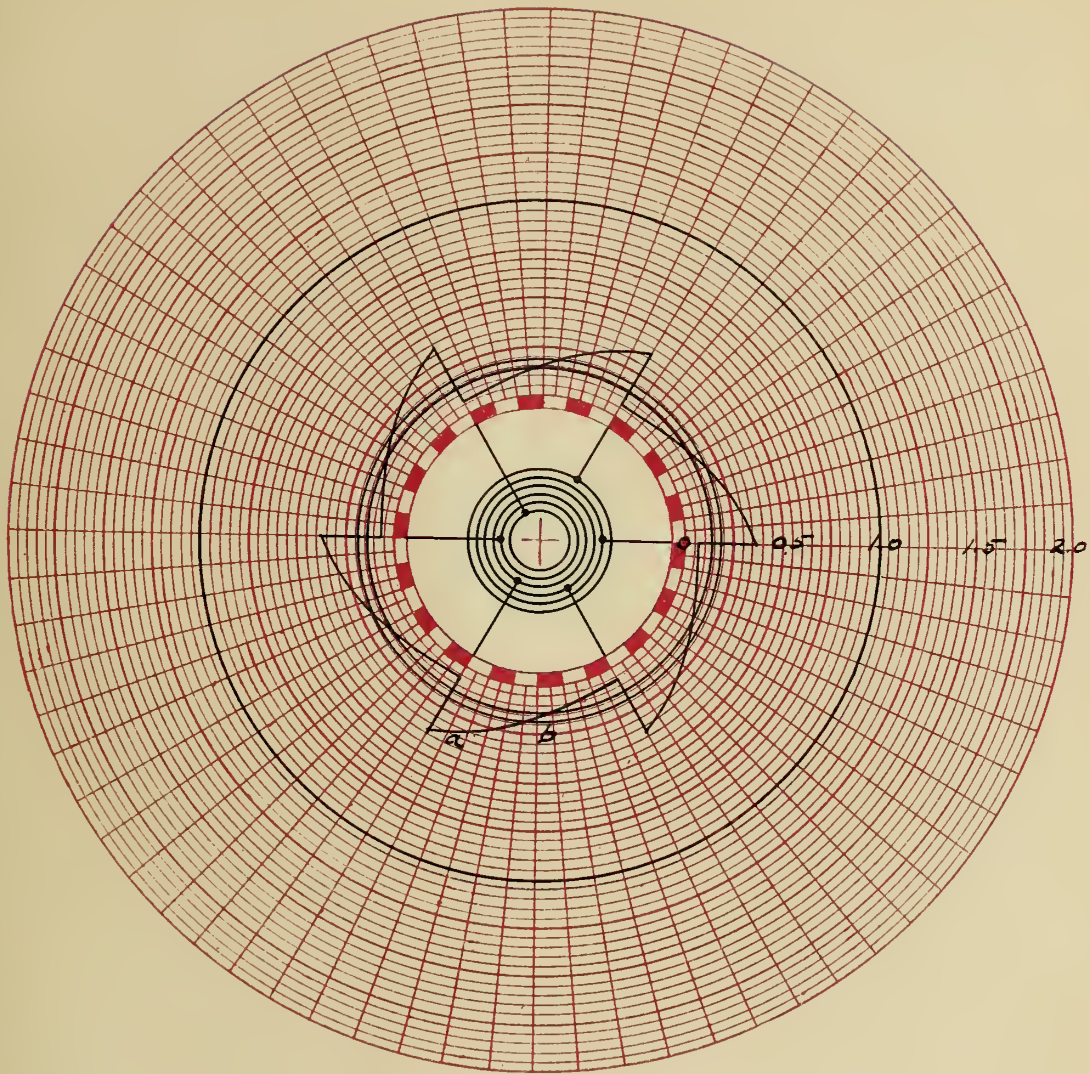
"n" 6. P.F. 90%

a--Distribution.

Max. .259 Min. o54

b--Average.

.II9



Distribution of Heating.

Six Phase.

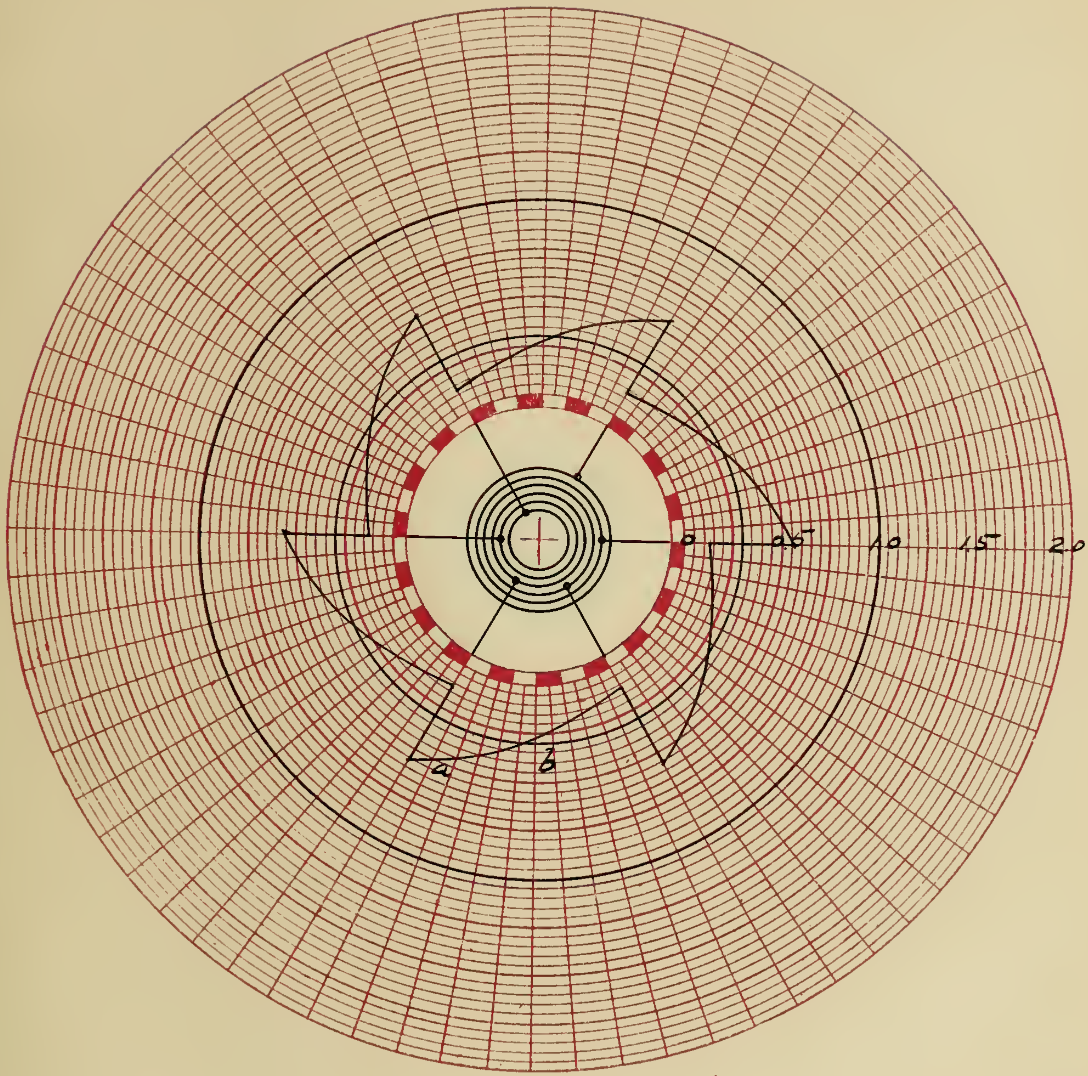
"n" 6. P.F. 80%

a--Distribution.

Max. .378 Min. .064

b--Average.

.I83



Distribution of Heating.

Six Phase.

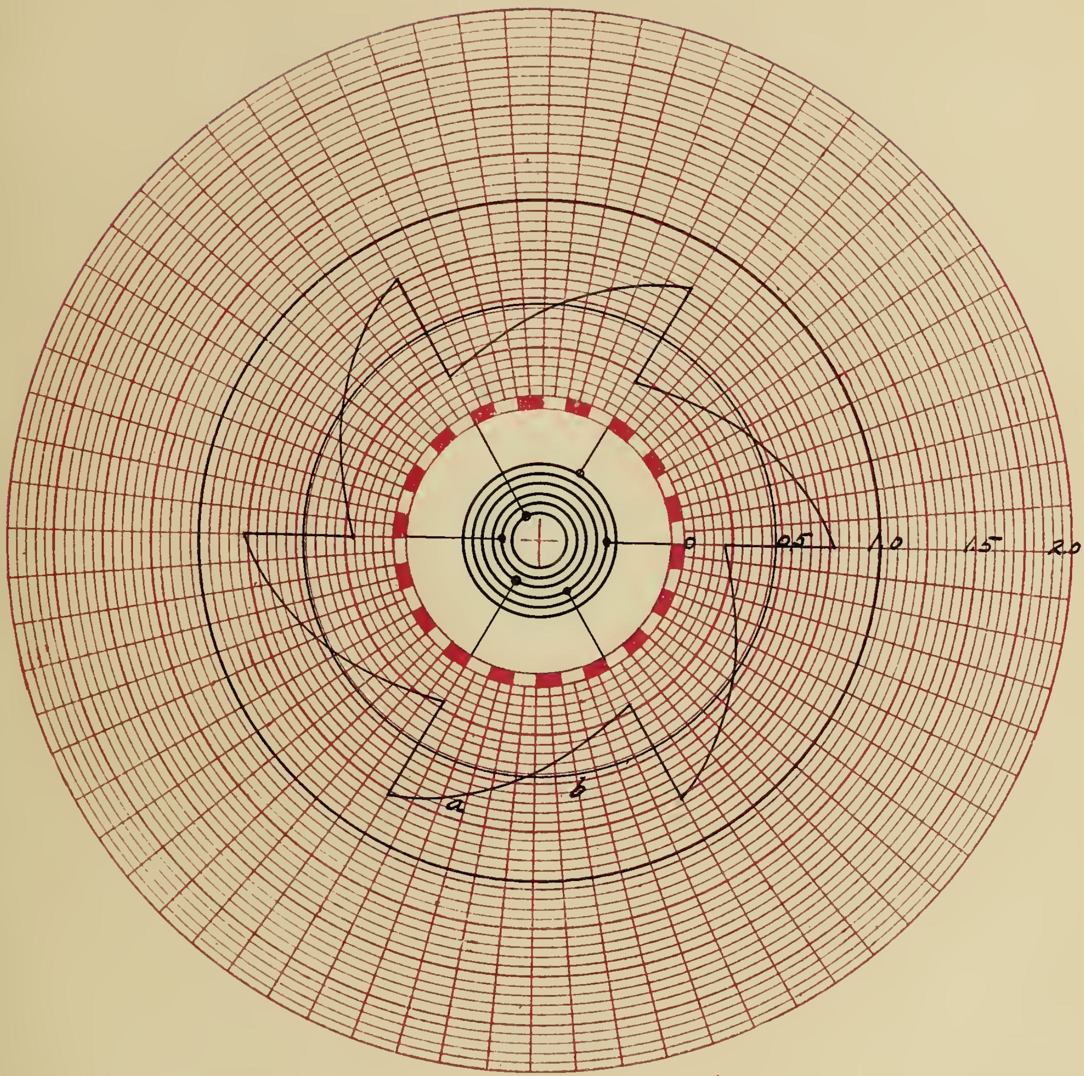
"n" 6. P.F. 70%

a--Distribution.

Max. .552 Min.,I20

b--Average.

.298



Distribution of Heating.

Six Phase.

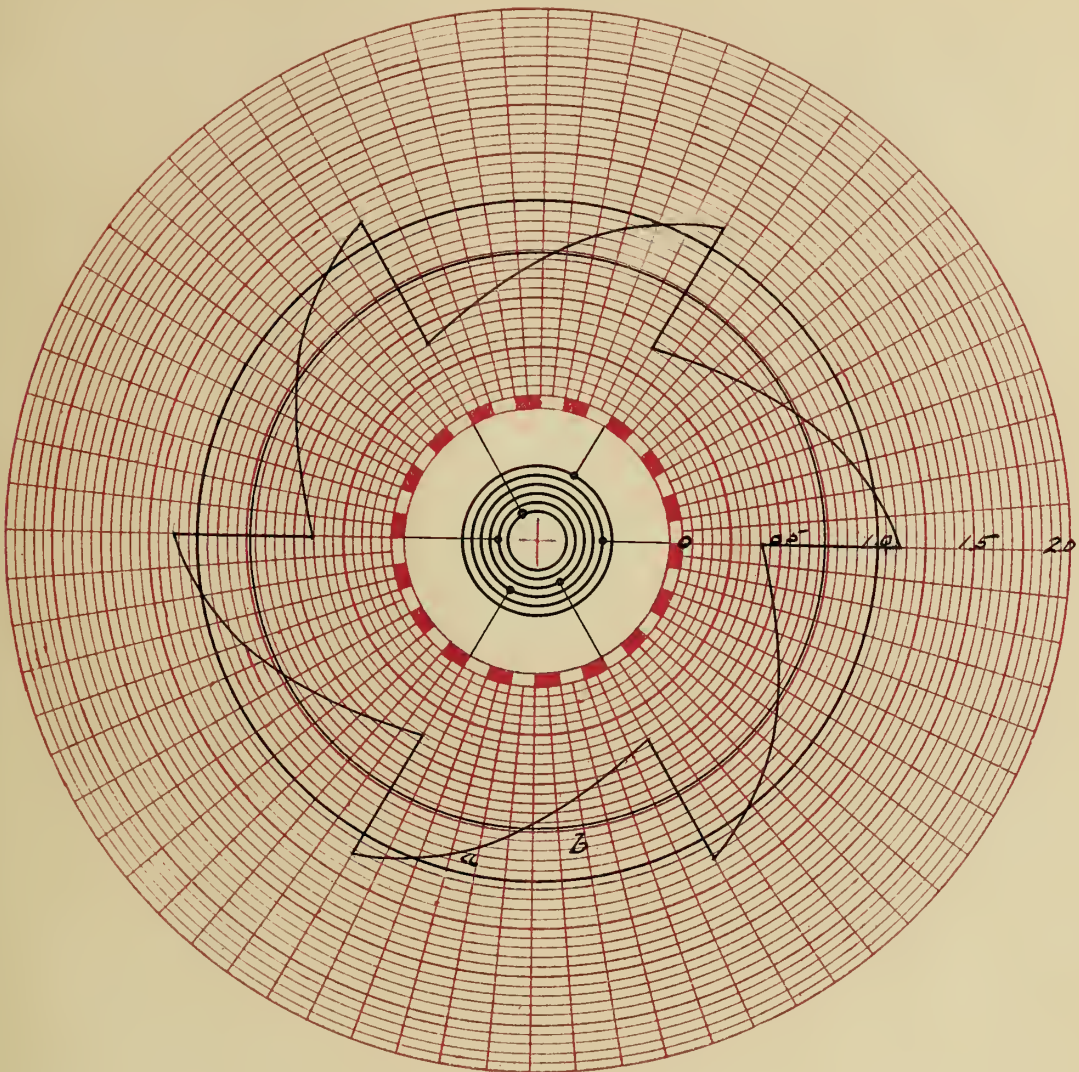
"n" 6. P.F. 60%

a--Distribution.

Max. .780 Min. 216

b--Average.

.460



Distribution of Heating.

Six Phase.

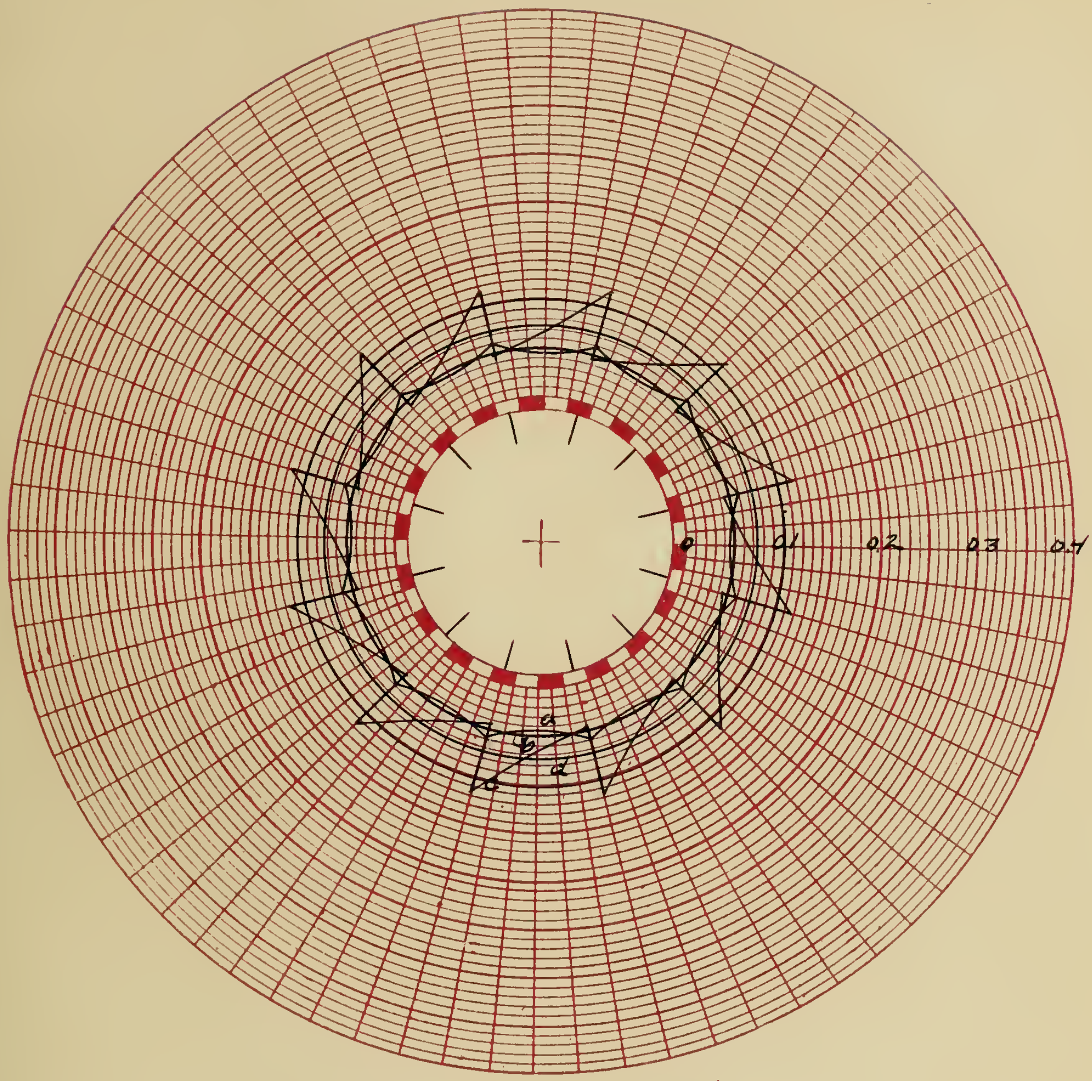
"n" 6 P.F. 50%

a--Distribution.

Max. I.I42 Min .404

b--Average.

.735



Distribution of Heating.

Twelve Phase.

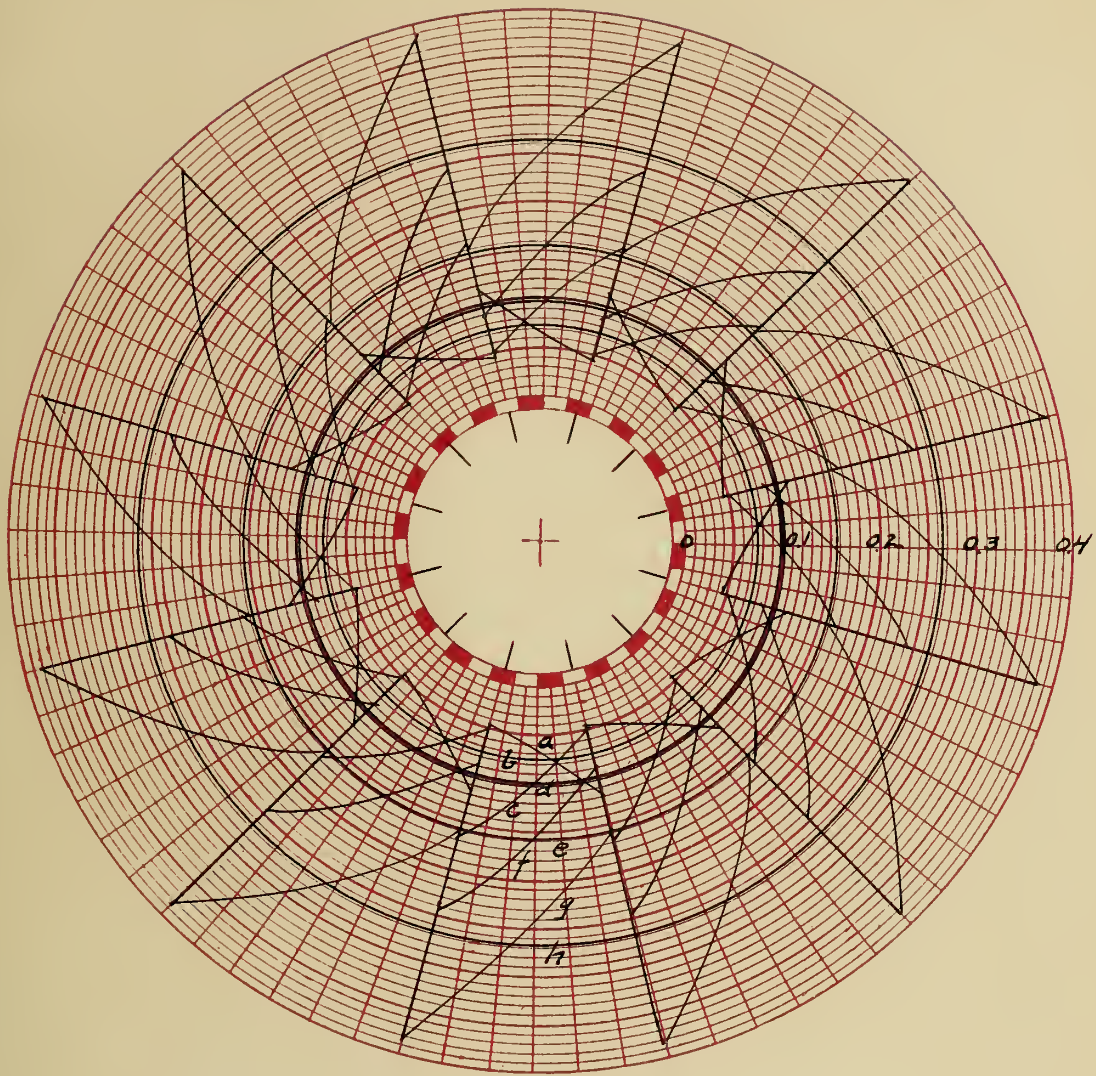
"n" I2. P.F. 100% & 95%

a c--Distribution.

Max. .059 Min. .046
.II6 .046

b d--Average.

.050
.072



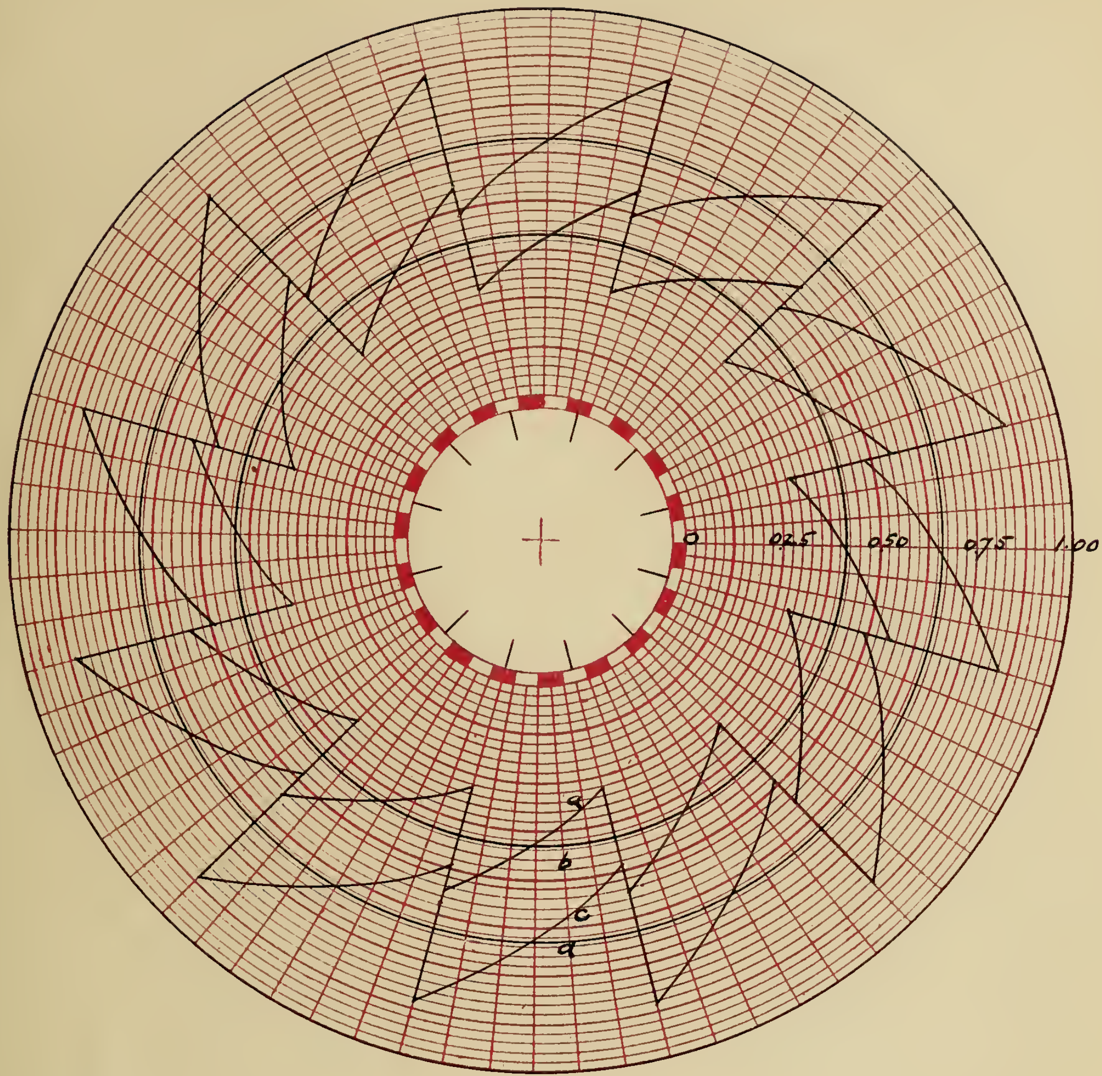
Distribution of Heating.

Twelve Phase.

"n" I2. P.F. -95%, 90%, 80%, 70%,

a-c-f-g--Distribution.

b-d-e-h--Average.



Distribution of Heating.

Twelve Phase.

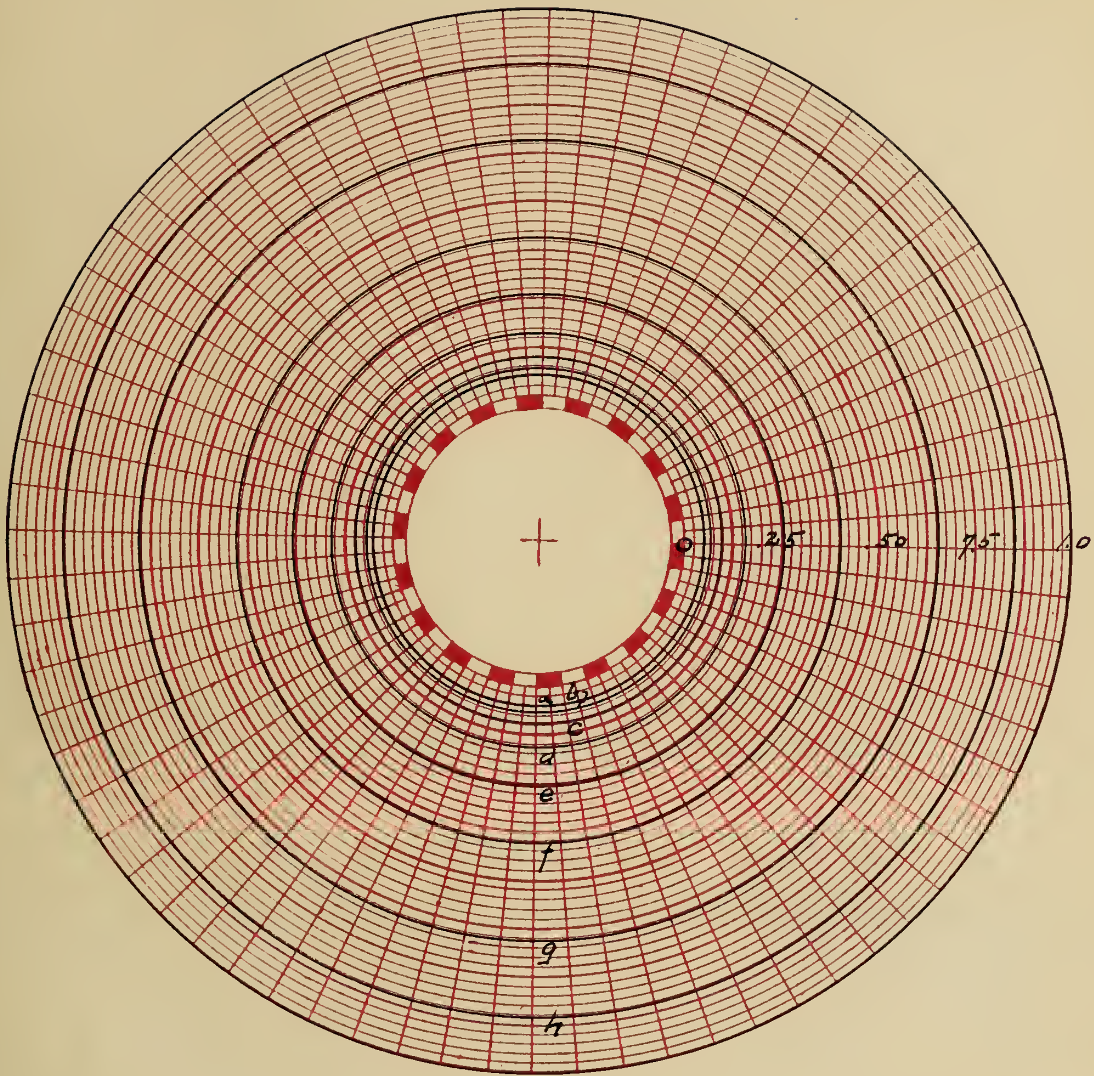
"n" I2 P.F. 60%&50%

a c--Distribution.

Max. .563 Min. .28I
.86I .493

b d--Average

.4I3
.668



Distribution of Heating.

Infinite Phase.

"n" P.F. varies.

Distribution equals Average.

a---100%

b----95%

c----90%

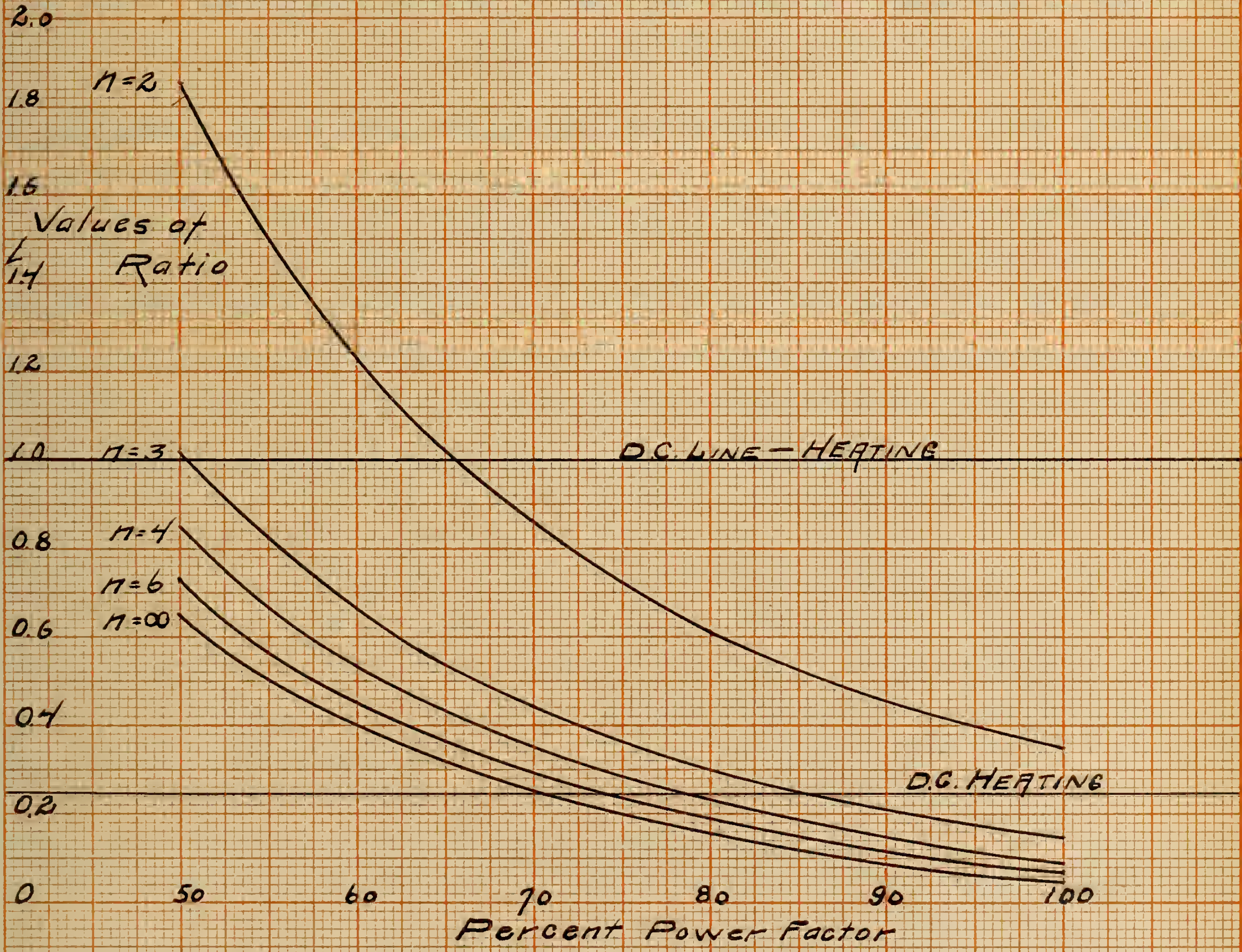
d----80%

e----70%

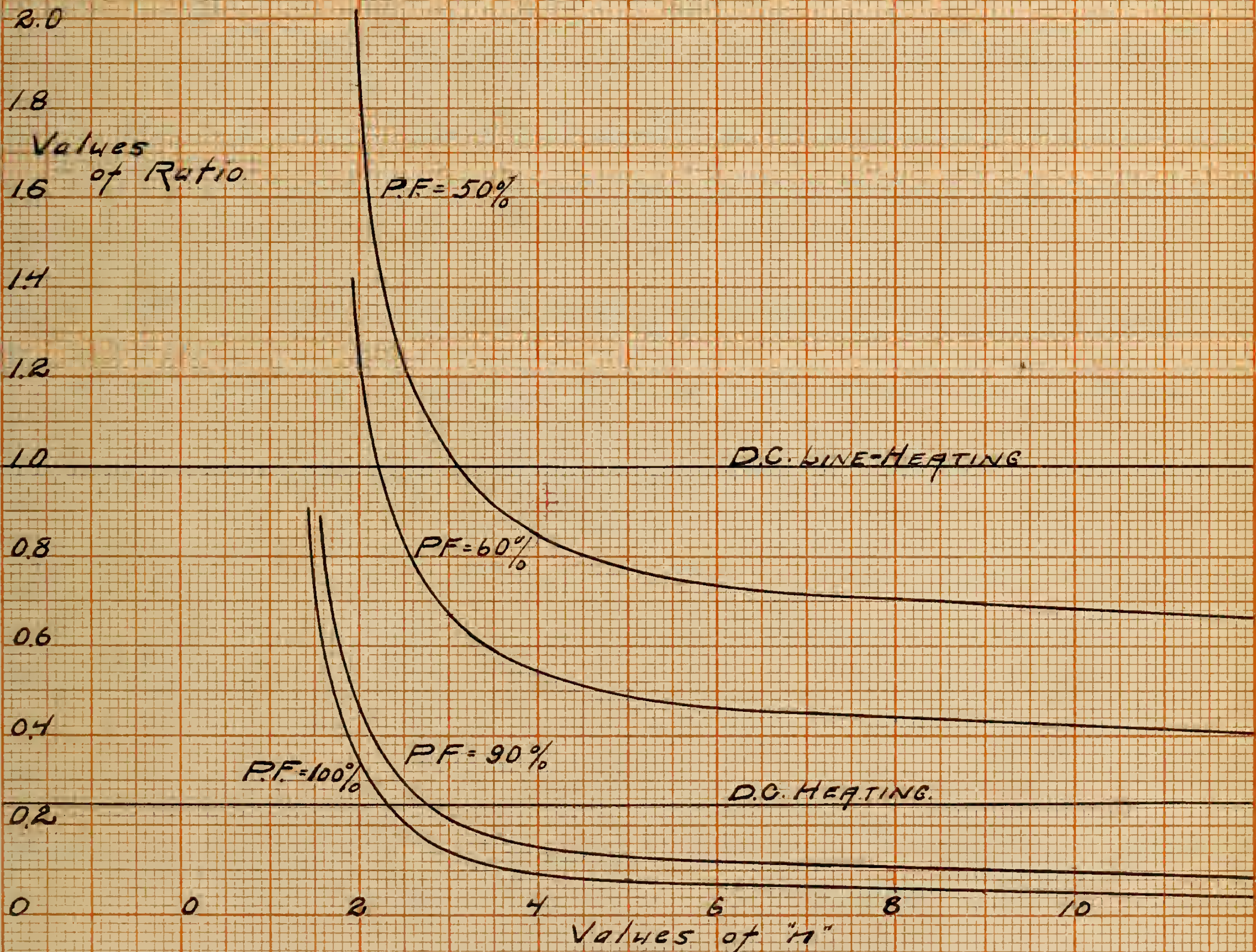
f----60%

g----50%

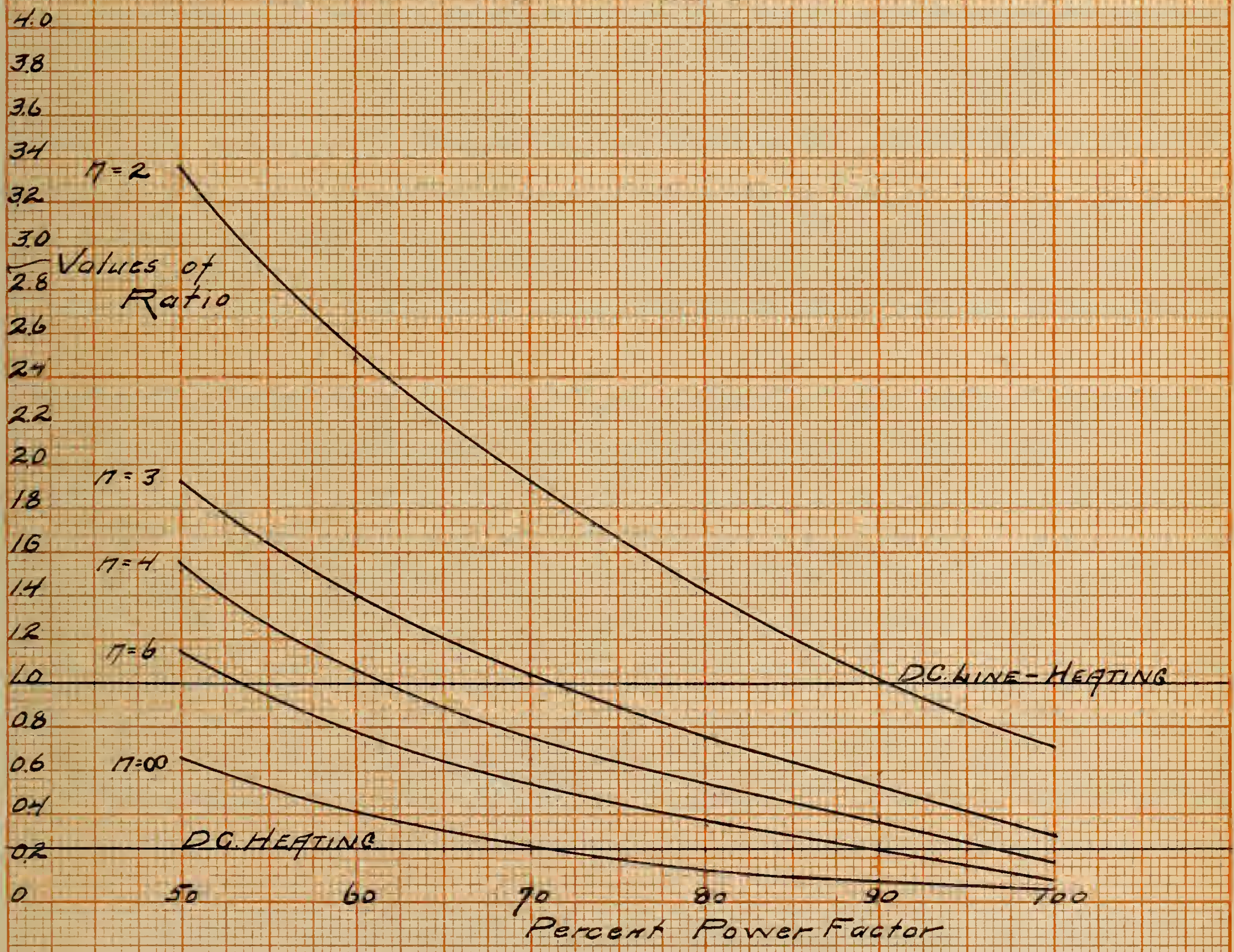
h-----5%(x.010)



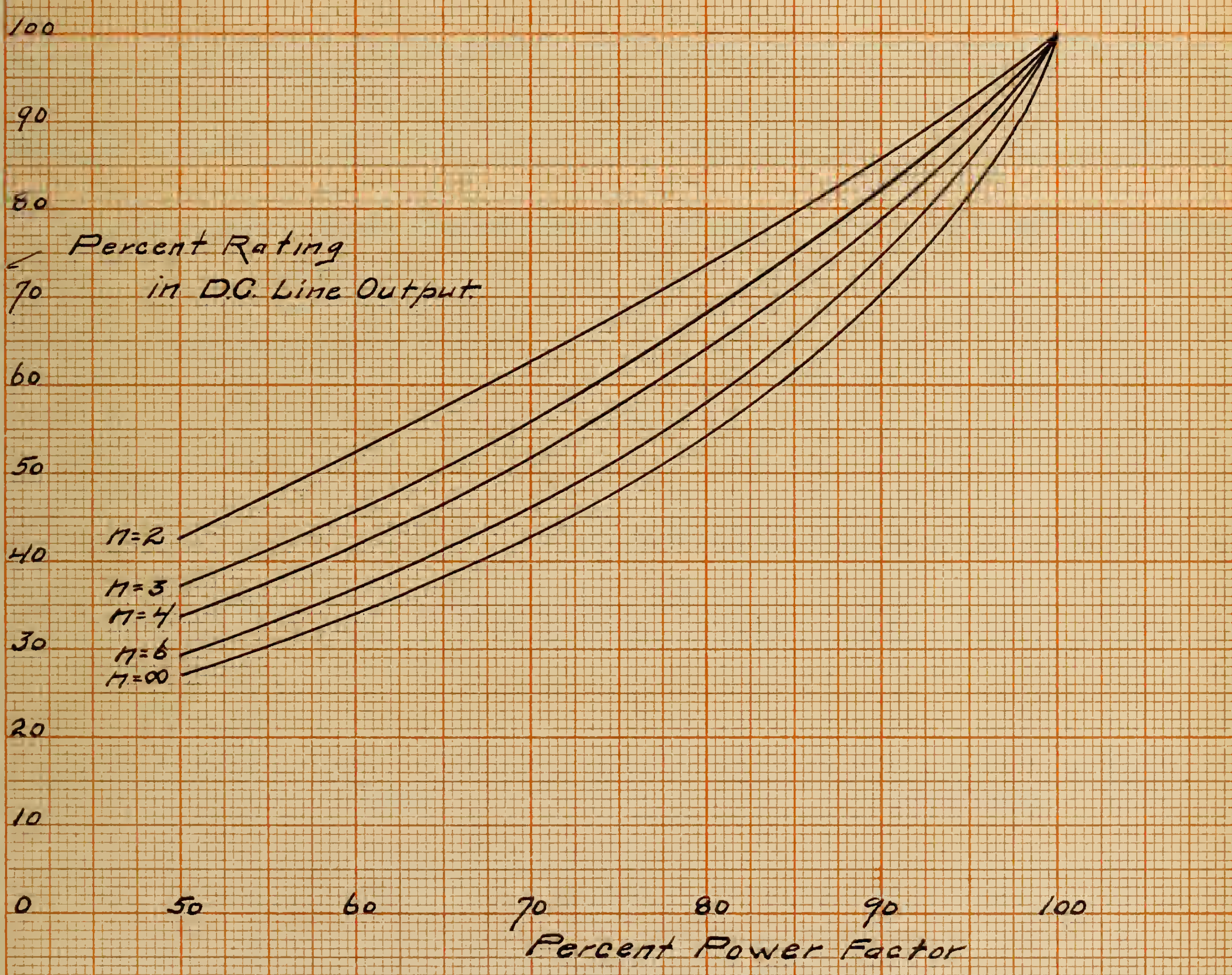
GRAFS SHOWING VARIATION
OF
AVERAGE HEATING RATIO WITH POWER FACTOR



GRAFS SHOWING VARIATION
OF
AVERAGE HEATING RATIO WITH PHASE RATING.



GRAFS SHOWING VARIATION
OF
MAXIMUM HEATING RATIO WITH POWER FACTOR



GRAFS SHOWING VARIATION
OF
PERMISSIBLE RATING WITH
POWER FACTOR
FOR SAME HEATING.